INVESTIGATIONS ON SHUNT ACTIVE POWER FILTER FOR POWER QUALITY IMPROVEMENT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Power Control and Drives

By

D. Pradeep kumar

Department of Electrical Engineering

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Under the Guidance of

Prof. P.C. Panda

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CERTIFICATE

This is to certify that the thesis entitled, **"Investigations On Shunt Active Power Filter For Power Quality Improvement"** submitted by Sri **D. Pradeep Kumar** in partial fulfillment of the requirements for the award of MASTER of Technology Degree in **Electrical Engineering** with specialization in **"Power Control and Drives"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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Dedicated To My Mother

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I feel a deep sense of gratitude for my father Sri.D.Rajireddy and mother Smt. Nirmala who formed a part of my vision and taught me the good things that really matter in life. I would like to thank my brother and other family members for their support.

An undertaking of this nature could never have been attempted with our reference to and inspiration from the works of others whose details are mentioned in references section. I acknowledge my indebtedness to all of them. Last but not the least, my sincere thanks to all of my friends who have patiently extended all sorts of help for accomplishing this undertaking.

CONTENTS

ABSTRACT

Most of the pollution issues created in power systems are due to the non-linear characteristics and fast switching of power electronic equipment. Power quality issues are becoming stronger because sensitive equipment will be more sensitive for market competition reasons, equipment will continue polluting the system more and more due to cost increase caused by the built-in compensation and sometimes for the lack of enforced regulations. Efficiency and cost are considered today almost at the same level. Active power filters have been developed over the years to solve these problems to improve power quality. Among which shunt active power filter is used to eliminate and load current harmonics and reactive power compensation.

In this work both PI controller based and fuzzy logic controlled, three-phase shunt active power filter to compensate harmonics and reactive power by nonlinear load to improve power quality is implemented for three-phase three wire systems. The advantage of fuzzy control is that it is based on linguistic description and does not require a mathematical model of the system. The compensation process is based on sensing line currents only, an approach different from conventional methods, which require sensing of harmonics or reactive power components of the load.

A MATLAB program has been developed to simulate the system operation. Various simulation results are presented under steady state conditions and performance of fuzzy and PI controllers is compared. Simulation results obtained shows that the performance of fuzzy controller is found to be better than PI controller. PWM pattern generation is based on carrier less hysteresis based current control to obtain the switching signals to the voltage sourced PWM converter.

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INTRODUCTION

Early equipment was designed to withstand disturbances such as lightning, short circuits, and sudden overloads without extra expenditure. Current power electronics (PE) prices would be much higher if the equipment was designed with the same robustness. Pollution has been introduced into power systems by nonlinear loads such as transformers and saturated coils; however, perturbation rate has never reached the present levels. Due to its nonlinear characteristics and fast switching, PE create most of the pollution issues. Most of the pollution issues are created due to the nonlinear characteristics and fast switching of PE. Approximately 10% to 20% of today’s energy is processed by PE; the percentage is estimated to reach 50% to 60% by the year 2010, due mainly to the fast growth of PE capability. A race is currently taking place between increasing PE pollution and sensitivity, on the one hand, and the new PE-based corrective devices, which have the ability to attenuate the issues created by PE, on the other hand.

Increase in such non-linearity causes different undesirable features like low system efficiency and poor power factor. It also causes disturbance to other consumers and interference in nearby communication networks. The effect of such non-linearity may become sizeable over the next few years. Hence it is very important to overcome these undesirable features.

Classically, shunt passive filters, consist of tuned LC filters and/or high passive filters are used to suppress the harmonics and power capacitors are employed to improve the power factor. But they have the limitations of fixed compensation, large size and can also exile resonance conditions.

Active power filters are now seen as a viable alternative over the classical passive filters, to compensate harmonics and reactive power requirement of the non-linear loads. The objective of the active filtering is to solve these problems by combining with a much-reduced rating of the necessary passive components.

Various topologies of active power filters have been developed so far [1-12]. The shunt active power filter based on current controlled voltage source type PWM converter has been proved to be effective even when the load is highly non-linear [1,4,11]. Most of the active filters developed are based on sensing harmonics [7,10,11] and reactive volt-ampere requirements of the non-linear load [1,3,12,17] and require complex control. A new scheme has been proposed in [10], in which the required compensating current is determined by sensing load current which is further modified by sensing line currents only [8,13]. An instantaneous reactive volt-ampere compensator and harmonic suppressor system is proposed

[13] without the use of voltage sensors but require complex hardware for current reference generator.

However, the conventional PI controller was used for the generation of a reference current template. The PI controller requires precise linear mathematical models, which are difficult to obtain and fails to perform satisfactorily under parameter variations, nonlinearity, load disturbance, etc.

Recently, fuzzy logic controllers (FLCs) have generated a good deal of interest in certain applications [18,19,21]. The advantages or FLCs over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle lion-linearity, and they are more robust than conventional nonlinear controllers.

In this work both PI and fuzzy logic controlled shunt active power filter for the harmonics and reactive power compensation of a nonlinear load are implemented. The control scheme is based on sensing line currents only; an approach different from convention ones, which arc based on sensing harmonics and reactive volt-ampere requirements of the nonlinear load. The three-phase currents/voltages are detected using only two current/voltage sensors. The DC capacitor voltage is regulated to estimate the reference current template. The role of the DC capacitor is described to estimate the reference current. A design criterion is described for the selection of power circuit components. Both the control schemed are compared and performance of both the controllers is investigated. A detailed simulation program of the schemes is developed to predict the performance for different conditions and simulink models also has been developed for the same for different parameters and operating conditions.

1.1. BACKGROUND

1.1.1. Power quality

The PQ issue is defined as “any occurrence manifested in voltage, current, or frequency deviations that results in damage, upset, failure, or misoperation of end-use equipment.” Almost all PQ issues are closely related with PE in almost every aspect of commercial, domestic, and industrial application. Equipment using power electronic devise are residential appliances like TVs, PCs etc. business and office equipment like copiers, printers etc. industrial equipment like programmable logic controllers (PLCs), adjustable speed drives (ASDs), rectifiers, inverters, CNC tools and so on. The Power Quality (PQ) problem can be detected from one of the following several symptoms depending on the type of issue involved.

- Lamp flicker
- Frequent blackouts
- Sensitive-equipment frequent dropouts
- Voltage to ground in unexpected
- Locations
- Communications interference
- Overheated elements and equipment.

PE are the most important cause of harmonics, interharmonics, notches, and neutral currents. Harmonics are produced by rectifiers, ASDs, soft starters, electronic ballast for discharge lamps, switched-mode power supplies, and HVAC using ASDs. Equipment affected by harmonics includes transformers, motors, cables, interrupters, and capacitors (resonance). Notches are produced mainly by converters, and they principally affect the electronic control devices. Neutral currents are produced by equipment using switched-mode power supplies, such as PCs, printers, photocopiers, and any triplets generator. Neutral currents seriously affect the neutral conductor temperature and transformer capability. Interharmonics are produced by static frequency converters, cyclo-converters, induction motors & arcing devices.

Equipment presents different levels of sensitivity to PQ issues, depending on the type of both the equipment and the disturbance. Furthermore, the effect on the PQ of electric power systems, due to the presence of PE, depends on the type of PE utilized. The maximum acceptable values of harmonic contamination are specified in IEEE standard in terms of total harmonic distortion.

Power electronics are alive and well in useful applications to overcome distribution system problems. Power electronics has three faces in power distribution: one that introduces valuable industrial and domestic equipment; a second one that creates problems; and, finally, a third one that helps to solve those problems. On one hand, power electronics and microelectronics have become two technologies that have considerably improved the quality of modern life, allowing the introduction of sophisticated energy-efficient controllable equipment to industry and home. On another hand, those same sensitive technologies are conflicting with each other and increasingly challenging the maintenance of quality of service in electric energy delivery, while at the same time costing billions of dollars in lost customer productivity.

1.1.2. Solutions to power quality problems

There are two approaches to the mitigation of power quality problems. The first approach is called load conditioning, which ensures that the equipment is made less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line-conditioning systems that suppress or counteract the power system disturbances. Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems. They are usually custom designed for the application. However, their performance is limited to a few harmonics, and they can introduce resonance in the power system. Among the different new technical options available to improve power quality, active power filters have proved to be an important and flexible alternative to compensate for current and voltage disturbances in power distribution systems. The idea of active filters is relatively old, but their practical development was made possible with the new improvements in power electronics and microcomputer control strategies as well as with cost reduction in electronic components. Active power filters are becoming a viable alternative to passive filters and are gaining market share speedily as their cost becomes competitive with the passive variety. Through power electronics, the active filter introduces current or voltage components, which cancel the harmonic components of the nonlinear loads or supply lines, respectively. Different active power filters topologies have been introduced and many of them are already available in the market.

1.1.3. Power filter topologies

Depending on the particular application or electrical problem to be solved, active power filters can be implemented as shunt type, series type, or a combination of shunt and series active filters (shunt-series type). These filters can also be combined with passive filters to create hybrid power filters.

The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal-but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase-shifted by 180°.

Series active power filters were introduced by the end of the 1980s and operate mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series-connected filter protects the consumer from an inadequate supply-voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply and for low-power applications and represents an economically attractive alternative to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side. In many cases, series active filters work as hybrid topologies with passive LC filters. If passive LC filters are connected in parallel to the load, the series active power filter operates as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than the power distribution system. The main advantage of this scheme is that the rated power of the series active filter is a small fraction of the load kVA rating, typically 5%. However, the apparent power rating of the series active power filter may increase in case of voltage compensation.

The series-shunt active filter is a combination of the series active filter and the shunt active filter. The shunt active filter is located at the load side and can be used to compensate for the load harmonics. On the other hand, the series portion is at the source side and can act as a harmonic blocking filter. This topology has been called the Unified Power Quality conditioner. The series portion compensates for supply voltage harmonics and voltage unbalances, acts as a harmonic blocking filter, and damps power system oscillations. The shunt portion compensates load current harmonics, reactive power, and load current unbalances. In addition, it regulates the dc link capacitor voltage. The power supplied or absorbed by the shunt portion is the power required by the series compensator and the power required to cover losses.

Hybrid power filters are a combination of active and passive filters. With this topology the passive filters have dynamic low impedance for current harmonics at the load side, increasing their bandwidth operation and improving their performance. This behavior is reached with only a small power rating PWM inverter, which acts as an active filter in series with the passive filter.

Multilevel inverters are being investigated and recently used for active filter topologies. Three-level inverters are becoming very popular today for most inverter applications, such as machine drives and power factor compensators. The advantage of multilevel converters is that they can reduce the harmonic content generated by the active filter because they can produce more levels of voltage than conventional converters (more than two levels). This feature helps to reduce the harmonics generated by the filter itself.

Another advantage is that they can reduce the voltage or current ratings of the semiconductors and the switching frequency requirements. The more levels the multilevel inverter has, the better the quality of voltage generated because more steps of voltage can be created.

1.1.4. Voltage source converters

Most of the active power filter topologies use voltage source converters, which have a voltage source at the dc bus, usually a capacitor, as an energy storage device. This topology, shown in Figure 1.1, converts a dc voltage into an ac voltage by appropriately gating the power semiconductor switches. Although a single pulse for each half cycle can be applied to synthesize an ac voltage, for most applications requiring dynamic performance, pulse width modulation (PWM) is the most commonly used today. PWM techniques applied to a voltage source inverter consist of chopping the dc bus voltage to produce an ac voltage of an arbitrary waveform. There are a large number of PWM techniques available to synthesize sinusoidal patterns or any arbitrary pattern. With PWM techniques, the ac output of the filter can be controlled as a current or voltage source device.

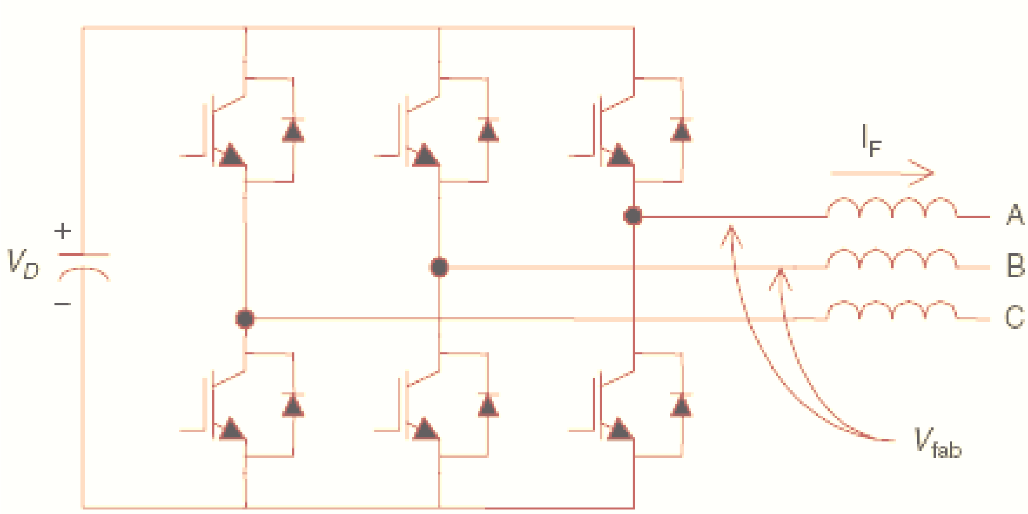

Figure 1.1.Voltage source converter topology for active filters.

Figure 1.2 shows the way PWM works by means of one of the simplest and most common techniques: the triangular carrier technique. It forces the output voltage v_a over a switching cycle, defined by the carrier period of V_{car}, to be equal to the average amplitude of the modulating wave V_a ref. The resulting voltages for a sinusoidal modulation wave contain a sinusoidal fundamental component $V_a(1)$ and harmonics of unwanted components. These unwanted components can be minimized using a frequency carrier as high as possible, but this depends on the maximum switching frequency of the semiconductors (IGBTs, GTOs, or IGCTs).

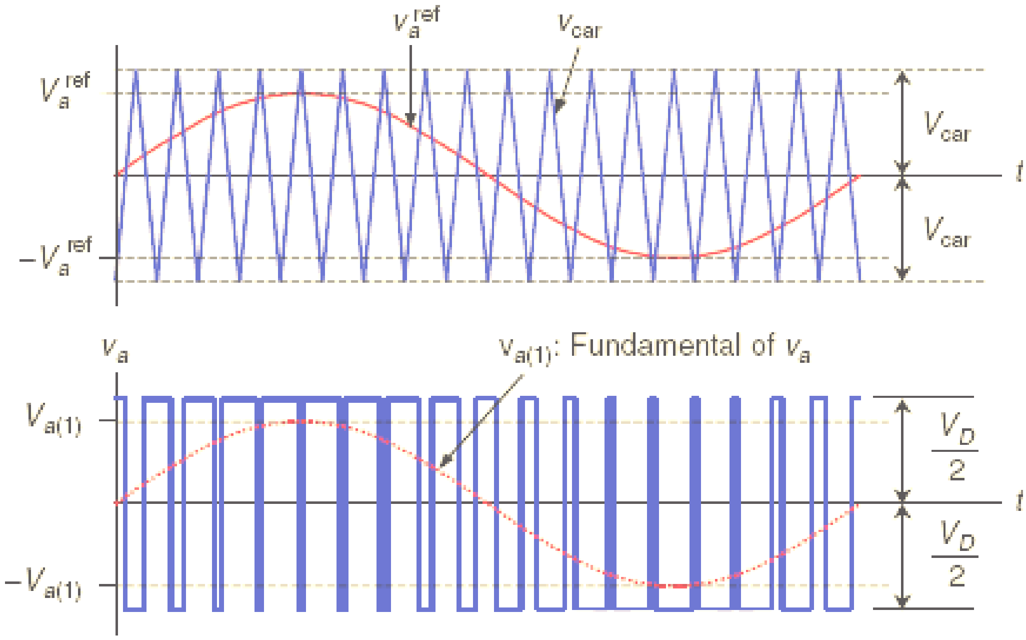

Figure.1.2. The PWM carrier Technique (triangular carrier).

The modulation strategy shown in Figure 1.3 uses a triangular carrier, which is one of many strategies applied today to control power inverters. Depending on the application (machine drives, PWM rectifiers, or active power filters), some modulation strategies are more suitable than others. The modulation techniques not only allow controlling the inverters as voltage sources but also as current sources. Figure 1.3 shows the compensating current generated for a shunt active power filter using three different modulation techniques for current-source inverters. These three techniques are periodical sampling (PS), hysteresis band (HB), and triangular carrier (TC). The PS method switches the power transistors of the active filter during the transitions of a square wave clock of fixed frequency: the sampling frequency. The HB method switches the transistors when the error exceeds a fixed magnitude: the hysteresis band. The TC method compares the output current error with a fixed amplitude and fixed triangular wave: the triangular carrier. Figure 1.3 shows that the HB method is the best for this particular waveform and application because it follows more accurately the current reference of the filter. When sinusoidal waves are required, the TC method has been demonstrated to be better.

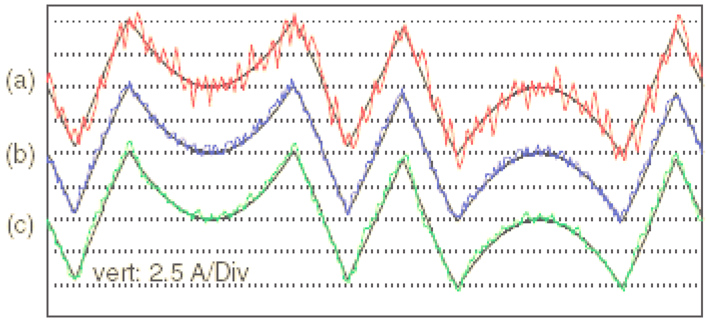

Figure.1.3. Current waveforms obtained using different modulation techniques for an active power filter: (a) PS method, (b) HB method, (c) TC method.

Voltage source converters are preferred over current source converter because it is higher in efficiency and lower initial cost than the current source converters [3, 4, 9]. They can be readily expanded in parallel to increase their combined rating and their switching rate can be increased if they are carefully controlled so that their individual switching times do not coincide. Therefore, higher-order harmonics can be eliminated by using converters without increasing individual converter switching rates.

1.1.5. Control strategies

Most of the active filters developed are based on sensing harmonics [7,10,11] and reactive volt-ampere requirements of the non-linear load. [4,12,17] and require complex control. In some active filters, both phase voltages and load currents are transformed into the α-β orthogonal quantities, from which the instantaneous real and reactive power. The compensating currents are calculated from load currents and instantaneous powers. The harmonic components of power are calculated using high pass filters in the calculation circuit. The control circuit of the dc capacitor voltage regulates the average value of the voltage to the reference value [4]. Reactive power compensation is achieved without sensing and computing the reactive current component of the load, thus simplifying the control circuit. Current control is achieved with constant switching frequency producing a better switching pattern. An active filter based on the instantaneous active and reactive current component in which current harmonics of positive and negative sequence including the fundamental current of negative sequence can be compensated. The system therefore acts as a harmonic and unbalanced current compensator. A comparison between the instantaneous active and reactive current component - method and the instantaneous active and reactive power method is realized [17].

A new scheme has been proposed in [10], in which the required compensating current is generated using simple synthetic sinusoid generation technique by sensing the load current. This scheme is further modified by sensing line currents only [8,13]. An instantaneous reactive volt-ampere compensator and harmonic suppressor system is proposed [13] without the use of voltage sensors but require complex hardware for current reference generator. The generated reference current is not a pure sine wave but stepped sine wave. Also, without the use of voltage sensors, the scheme generates balanced sine wave reference currents but do not compensate reactive power completely (if source voltage is unbalanced/distorted) due to waveform difference between voltage and current [14]).

Control scheme based on sensing line currents is described in [2]. The 3-phase currents/voltages are detected using only two current/voltage sensors compared to three used in [8,16]. DC capacitor voltage is regulated to estimate the reference current template. Selection of dc capacitor value has been described in [4,7,13].

Conventional solutions for controller requirements were based on classical control theory or modern control theory. Widely used classical control theory based design of PID family controllers requires precise linear mathematical models. The PID family of controllers failed to perform satisfactorily under parameter variation, non linearity, load disturbance, etc.[18]

During the past several years, fuzzy control has emerged as one of the most active and fruitful areas for research in the applications of fuzzy set theory, especially in the realm of industrial processes, which do not lend themselves to control by conventional methods because of a lack of quantitative data regarding the input-output relations. Fuzzy control is based on fuzzy logic-a logical system that is much closer in spirit to human thinking and natural language than traditional logical systems. The fuzzy logic controller (FLC) based on fuzzy logic provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy[19,21]. Recently, fuzzy logic controllers (FLC's) have generated a good deal of interest in certain applications. The advantages of FLC's over the conventional controllers are:

1. It does not need accurate mathematical model;
2. It can work with imprecise inputs;
3. It can handle nonlinearity, and

4. It is more robust than conventional nonlinear controllers.

1.2. OBJECTIVE

In modern electrical distribution systems there has been a sudden increase of single phase and three-phase non-linear loads. These non-linear loads employ solid state power conversion and draw non-sinusoidal currents from AC mains and cause harmonics and reactive power burden, and excessive neutral currents that result in pollution of power systems. They also result in lower efficiency and interference to nearby communication networks and other equipments. Active power filters have been developed to overcome these problems. Shunt active filters based on current controlled PWM converters are seen as viable solution. The techniques that are used to generate desired compensating current are based on instantaneous extraction of compensating commands from the distorted currents or voltage signals in time domain. Time domain compensation has fast response, easy implementation and less computation burden compared to frequency domain.

In this work both PI and fuzzy logic controlled shunt active power filter for the harmonics and reactive power compensation of a nonlinear load are implemented. Both controllers performance under certain conditions and different system parameters is studied. The advantages of fuzzy controllers over conventional controllers like PI controllers are that they do not need accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, load disturbances etc.

1.3. THESIS OUTLINE

The body of this thesis consists of the following seven chapters including first chapter:

- In Chapter 2, a description of the structure of the shunt active power filter, the basic compensation principle, how reference source current is estimated and role of DC side capacitor is given.
- Chapter 3 gives the PI control scheme of shunt active power filter in which DC voltage control loop design n how to select PI controller parameters is presented.
- Chapter 4 deals with the fuzzy logic, fuzzy login controllers and implementation of fuzzy control scheme for shunt active power filter. In this chapter basic fuzzy algorithm and design of control rules is also described.
- The entire active filter system is composed mainly of a three-phase source, a non-linear load, a voltage source PWM converter, and a PI or fuzzy controller. All these components modeling is described separately in chapter 5.

- In chapter 6, simulation results are put and discussed in detail. Both PI and fuzzy controller performances are compared under certain conditions.
- The conclusions of the thesis and recommendations for future work are summarized in Chapter 7.

Chapter 2

SHUNT ACTIVE POWER FILTER

Basic compensation principle

Estimation of reference current

Role of DC side capacitor

Selection of L_c and $V_{dc,ref}$

Design of DC side capacitor (C_{dc})

SHUNT ACTIVE POWER FILTER

The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal-but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase-shifted by 180°.

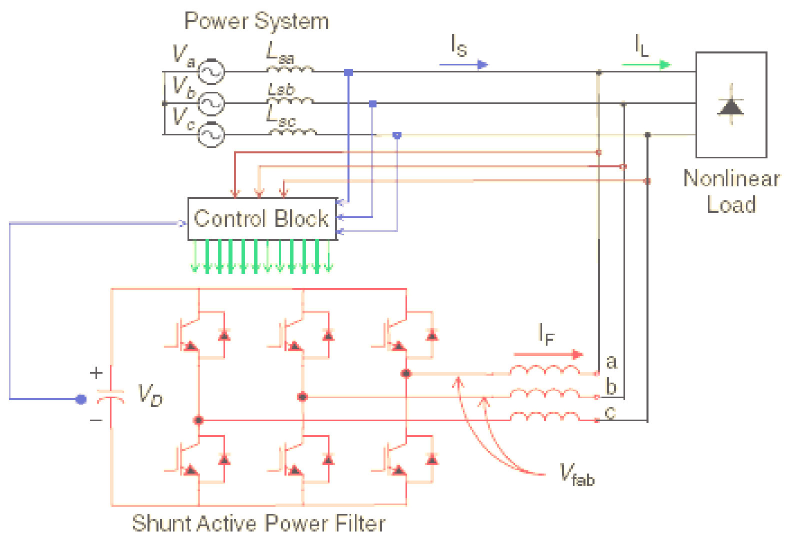

Figure.2.1.Shunt active power filter topology.

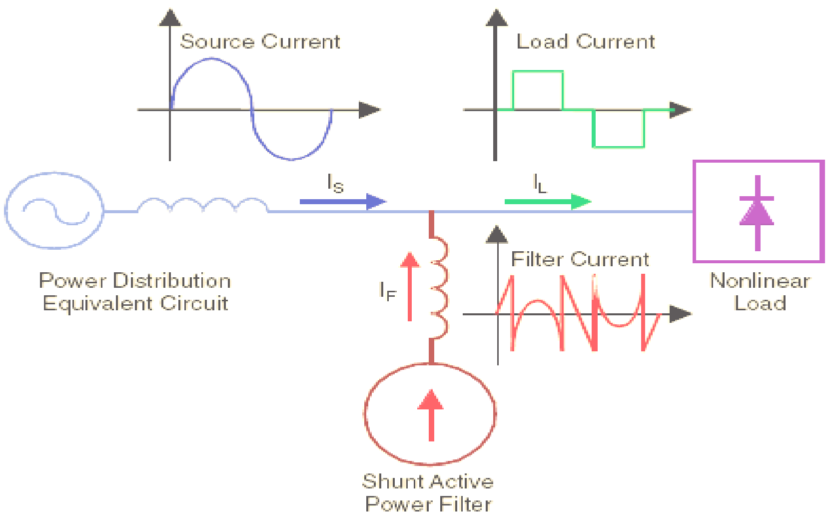

Figure.2.2. Filter current IF generated to compensate load-current harmonics.

Figure 2.1 shows the connection of a shunt active power filter and Figure 2.2shows how the active filter works to compensate the load harmonic currents.

2.1. BASIC COMPENSATION PRINCIPLE

Figure 2.3. shows the basic compensation principle of a shunt active power filter. It is controlled to draw / supply a compensating current i_c from / to the utility, so that it cancels current harmonics on the AC side, and makes the source current in phase with the source voltage. Figure.2.4. shows the different waveforms. Curve A is the load current waveform and curve B is the desired mains current. Curve C shows the compensating current injected by the active filter containing all the harmonics, to make mains current sinusoidal.

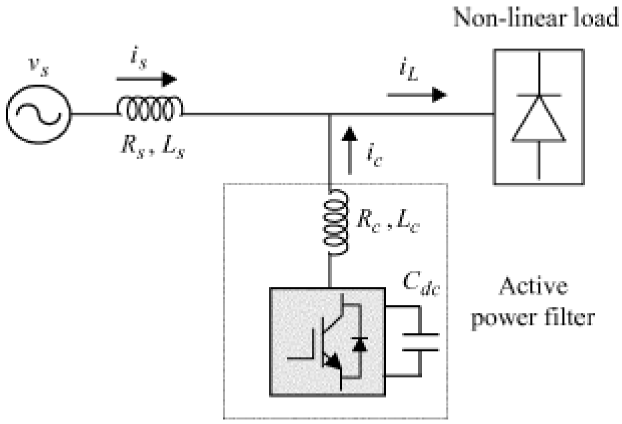

Figure.2.3.Shunt active power filter Basic compensation principle.

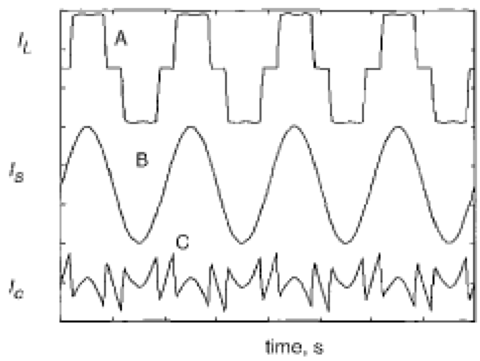

Figure.2.4.Shunt active power filter-Shapes of load, source and desired filter current wave forms.

2.2. ESTIMATION OF REFERENCE SOURCE CURRENT

From Figure.2.1.1, the instantaneous currents can be written as

$$i_s(t) = i_l(t) - i_c(t) \tag{2.2.1}$$

Source voltage is given by

$$v_s(t) = v_m \sin \omega t \tag{2.2.2}$$

If a non-linear load is applied, then the load current will have a fundamental component and harmonic components which can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= I_1 \sin(n\omega t + \phi_1) + \sum_{n=2}^{\infty} \sin(n\omega t + \phi_n) \tag{2.2.3}$$

The instantaneous load power can be given as

$$P_L(t) = v_s(t) * i_l(t)$$

$$= V_m I_1 \sin^2 \omega t * \cos\phi_1 + v_m I_1 \sin\omega t * \cos\omega t * \sin\phi_1 + V_m \sin\omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \tag{2.2.4}$$

$$= P_f(t) + P_r(t) + P_h(t) \tag{2.2.5}$$

From (2.2.4), the real (fundamental) power drawn by the load is

$$P_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t) \tag{2.2.6}$$

From (2.2.6), the source current supplied by the source, after compensation is

$$i_s(t) = P_f(t) / v_s(t) = I_1 \cos\phi_1 \sin\omega t = I_m \sin\omega t$$

Where $I_{sm} = I_1 \cos\Phi_1$.

There are also some switching losses in the PWM converter, and hence the utility must supply a small overhead for the capacitor leakage and converter switching losses in addition to the real power of the load. The total peak current supplied by the source is therefore

$$I_{sp} = I_{sm} + I_{sl} \tag{2.2.7}$$

If the active filter provides the total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current:

$$i_c(t) = i_L(t) - i_s(t) \tag{2.2.8}$$

Hence, for accurate and instantaneous compensation of reactive and harmonic power it is necessary to estimate, i.e. the fundamental component of the load current *as* the reference current.

2.2. ESTIMATION OF REFERENCE SOURCE CURRENT

The peak value of the reference current I_{sp} can be estimated by controlling the DC side capacitor voltage. Ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage, irrespective of the load current nature. The desired source currents, after compensation, can be given as

$$i_{sa}^{*} = I_{sp} \sin \omega t$$

$$i_{sb}^{*} = I_{sp} \sin(\omega t - 120^{0})$$

$$i_{sc}^{*} = I_{sp} \sin(\omega t + 120^{0})$$

Where I_{sp} ($=I_1 \cos\Phi_1 + I_{sl}$) the amplitude of the desired source current, while the phase angle can be obtained from the source voltages. Hence, the waveform and phases of the source currents are known, and only the magnitudes of the source currents need to be determined. This peak value of the reference current has been estimated by regulating the DC side capacitor voltage of the PWM converter. This capacitor voltage is compared with a reference value and the error is processed in a fuzzy controller. The output of the fuzzy controller has been considered as the amplitude of the desired source current, and the reference currents are estimated by multiplying this peak value with unit sine vectors in phase with the source voltages[6].

2.3. ROLE OF DC SIDE CAPACITOR

The DC side capacitor serves two main purposes: (i) it maintains a DC voltage with small ripple in steady state, and (ii) serves as an energy storage element to supply real power difference between load and source during the transient period. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value.

However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation or the active filter, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load. If the DC capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again.

Thus, in this fashion the peak value or the reference source current can be obtained by regulating the average voltage of the DC capacitor. A smaller DC capacitor voltage than the reference voltage means that the real power supplied by the source is not enough to supply the load demand. Therefore, the source current (i.e. the real power drawn from the source) needs to be increased, while a larger DC capacitor voltage than the reference voltage tries to decrease the reference source current. This change in capacitor voltage has been verified from the simulation results.

The real/reactive power injection may result in the ripple voltage of the DC capacitor. A low pass filter is generally used to filter these ripples, which introduce a finite delay. To avoid the use of this low pass filter the capacitor voltage is sampled at the zero crossing of the source voltage. A continuously changing reference current makes the compensation non-instantaneous during transient. Hence, this voltage is sampled at the zero crossing of one of the phase voltage, which makes the compensation instantaneous. Sampling only twice in cycle as compared to six times in a cycle leads to a slightly higher DC capacitor voltage rise/dip during transients, but settling time is less.

The design of the power circuit includes three main parameters:

- Selection of filter inductor, L_c.
- Selection of DC side capacitor, C_{dc}.
- Selection of reference value of DC side capacitor voltage, $V_{dc,ref}$.

2.4. SELECTION OF L_c AND $V_{dc,ref}$

The design of these components is based on the following assumptions:

1. The AC source voltage is sinusoidal.
2. To design of L_c, the AC side line current distortion is assumed to be 5%.
3. Fixed capability of reactive power compensation of the active filter.
4. The PWM converter is assumed to operate in the linear modulation mode (i.e. $0 \le m_a \le 1$).

As per the compensation principle, the active filter adjusts the current i_{c1} to compensate the reactive power of the load [2]. If the active filter compensates all the fundamental reactive power of the load, i_{s1} will be in phase and i_{c1} should be orthogonal to V_s**,** as shown in Fig.2.5. (the 1 stands here for the fundamental component).

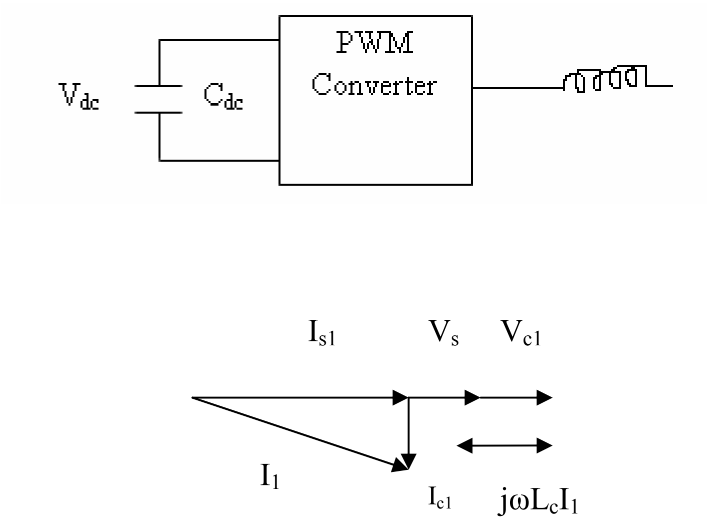

Figure.2.5. Active power filter and its phasor diagram

The three-phase reactive power delivered from the active filter can be calculated from a vector diagram

$$Q_{c1} = 3V_s I_{c1} = 3V_s V_{c1} / \omega L_c (1 - (V_s / V_{c1})) \qquad (2.4.1)$$

i.e. the active filter can compensate the reactive power from the utility only when $V_{c1} > V_s$.
If the PWM converter is assumed to operate in the linear modulation mode (i.e. $0 \leq m_a \leq 1$**)**, the amplitude modulation factor m_a is

$$m_a = v_m / (V_{dc} / 2)$$

Where $v_m = \sqrt{2}\, V_c$, and hence $V_{dc} = 2\sqrt{2}\, V_{c1}$ for $m_a = 1$.

The filter inductor L_c is also used to filter the ripples of the converter current, and hence the design of L_c is based on the principle of harmonic current reduction. The ripple current of the PWM converter can be given in terms of the maximum harmonic voltage, which occurs at the frequency $m_f\omega$:

$$I_{ch(mf\omega)} = V_{ch(mf\omega)} / m_f \omega L_c \qquad (2.4.2)$$

By solving (2.4.1) and (2.4.2) simultaneously, the value of L_c, and V_{c1} (i.e.V_{dc}*)* can be calculated. V_{c1}, and hence V_{dcref}, must be set according to the capacity requirement of the system (i.e. $V_s \leq V_{c1} \leq 2V_s$**)**. As the switching frequency is not fixed with the hysteresis controller, a practically feasible value of 10 kHz has been assumed.

2.5. DESIGN OF DC SIDE CAPACITOR (C_{dc})

The design of the DC side capacitor is based on the principle of instantaneous power flow. The selection of C_{dc} can be governed by reducing the voltage ripple [2]. As per the specification of the peak to peak voltage ripple ($V_{dc\ p\text{-}p(max)}$) and rated filter current ($I_{c1,rated}$), the DC side capacitor C_{dc} can be found from equation

$$C_{dc} = (\pi * I_{c1,rated})/(\sqrt{3}\omega V_{dc,p-p(\max)}) \tag{2.5}$$

Chapter 3

PI CONTROL SCHEME

Dc voltage control loop

Transfer function of PWM converter

Selection of PI controller parameters

PI CONTROL SCHEME

The complete schematic diagram of the shunt active power filter is shown in figure 3.1. While figure 3.2.gives the control scheme realization. The actual capacitor voltage is compared with a set reference value.

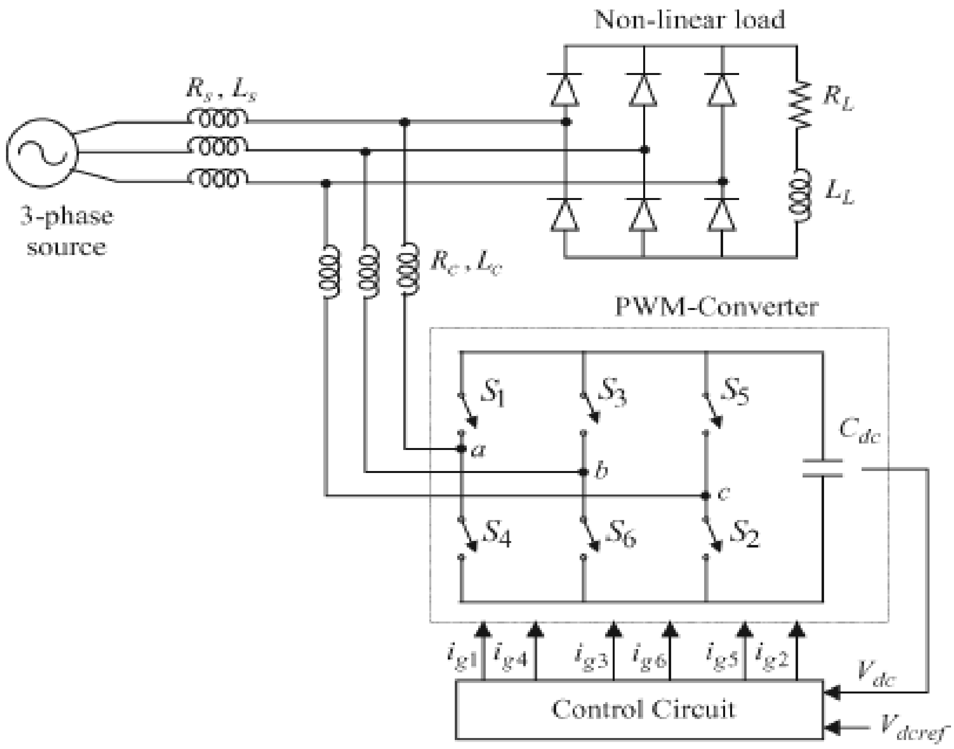

Figure .3.1. Schematic diagram of shunt active filter.

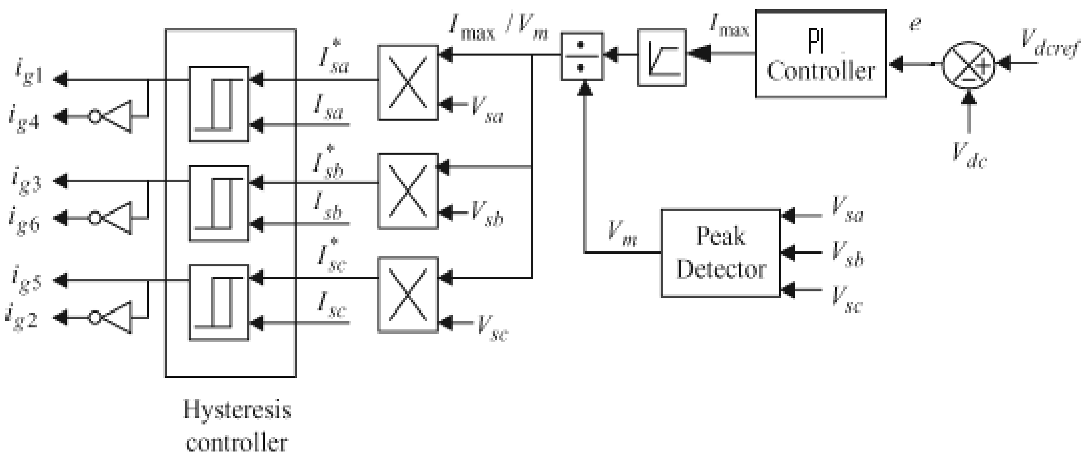

Figure .3.2. APF Control scheme with PI controller.

The error signal is fed to PI controller. The output of PI controller has been considered as peak value of the reference current. It is further multiplied by the unit sine vectors (u_{sa}, u_{sb}, and u_{sc}) in phase with the source voltages to obtain the reference currents (i_{sa}^*, i_{sb}^*, and i_{sc}^*). These reference currents and actual currents are given to a hysteresis based, carrierless PWM current controller to generate switching signals of the PWM converter[2]. The difference of reference current template and actual current decides the operation of switches. To increase current of particular phase, the lower switch of the PWM converter of that particular phase is switched on, while to decrease the current the upper switch of the particular phase is switched on. These switching signals after proper isolation and amplification are given to the switching devices. Due to these switching actions current flows through the filter inductor L_c, to compensate the harmonic current and reactive power of the load, so that only active power drawn from the source.

3.1. DC VOLTAGE CONTROL LOOP

The block diagram of the voltage control loop is shown in figure 3.3. Where, G_c is the gain of the PI controller and K_c is the transfer function of the PWM converter.

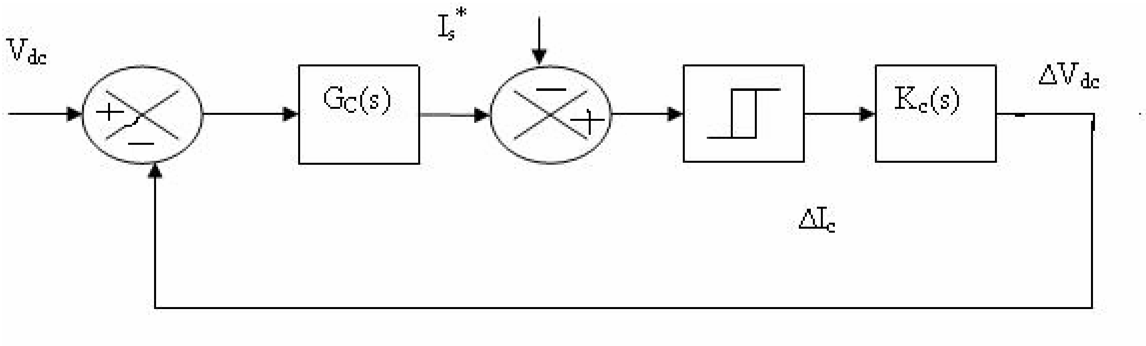

Figure.3.3.Block diagram of voltage control loop.

3.2 TRANSFER FUNCTION OF PWM CONVERTER (K_C)

The derivation between input (ac link) and output (dc link) quantities of the PWM converter is obtained by equating average rate of change of energy associated. Equating the average rate of change of energy quantities of input and output side of the PWM converter

$$P_{cap} = P_{conv} - P_{ind} \tag{3.2.1}$$

In order to linearize the power equation a small perturbation ΔI_c is applied in the input filter current of converter I_c, about a steady state operating point I_{co}, the average dc link voltge will also get perturbed by a small amount ΔV_{dc}, about its steady state operating point V_{dco} (V_{dcref}).

The transfer function of the PWM converter for a particular operating point can be obtained from (3.1) as

$$K_c = \frac{V_{dc}}{I_c} = \frac{3[V_s - L_c I_{co} s - 2I_{co} R_c]}{C_{dc} V_{dco} s} \tag{3.2.2}$$

3.3. SELECTION OF PI CONTROLLER PARAMETERS

A proportional-integral-derivative controller (PID controller) is control loop feed back mechanism used in industrial control systems. In an industrial process a PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. The PID controller calculation (algorithm) involves three separate modes; the Proportional mode, the Integral mode and Derivative mode. The proportional mode determines the reaction to the current error, the integral mode determines the reaction based on recent errors and the derivative mode determines the reaction based on the rate by which the error has been changing. The weighted sum of the three modes is outputted as a corrective action to a control element such as a control valve or heating element. By adjusting constants in the PID controller algorithm the PID can provide individualized control specific to process requirements including error responsiveness, overshoot of set point and system oscillation. Some applications may require only using one or two modes to provide the appropriate system control. A PID controller will be called a PI, PD, P or I controller in the absence of respective control actions. PI controllers are particularly common, since derivative action is very sensitive to measurement noise.

Proportional mode responds to a change in the process variable proportional to the current measured error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain or proportional sensitivity.

With integral mode, the controller output is proportional to the amount and duration of the error signal. The integral mode algorithm calculates the accumulated proportional offset over time that should have been corrected previously (finding the offset's integral). While this will force the controller to approach the set point quicker than a proportional controller alone and eliminate steady state error, it also contributes to system instability as the controller will always be responding to past values. This instability causes the process to overshoot the set point since the integral value will continue to be added to the output value, even after the process variable has reached the desired set point.

The characteristic equation of the voltage control loop is used to obtain the constants of PI controller in this case, can be written as [2]:

$$1 + (K_p + \frac{K_i}{s}) \frac{3[V_s - L_c I_{co} s - 2 I_{co} R_c]}{C_{dc} V_{dco} s} = 0 \tag{3.3}$$

Thus a second order transfer function can be found for the closed loop system. This characteristic equation is used to found the components of PI controller. The analysis of this characteristic equation shows that K_p determines the voltage response and K_i defines the damping factor of the voltage loop. The current controller has been designed on the basis of 5% overshoot, to step the change in the amplitude of current reference.

Chapter 4

FUZZY CONTROL SCHEME

Basic fuzzy algorithm

Design of control rules

FUZZY CONTROL SCHEME

Fig. 4. (1) shows the block diagram of the implemented fuzzy logic control scheme of a shunt active power filter. Fig.4. (2) shows the schematic diagram of the control algorithm. In order to implement the control algorithm of a shunt active power filter in closed loop, thee DC side capacitor voltage is sensed and then compared with a reference value. The obtained error *e* (=$V_{dc,ref}$-$V_{dc,act}$) and the change of error signal *ce(n)*=e(n)-e(n-1) at the nth sampling instant as inputs for the fuzzy processing. The output of the fuzzy controller after a limit is considered *as* the amplitude of the reference current I_{max} takes care of the active power demand of load and the losses in the system.

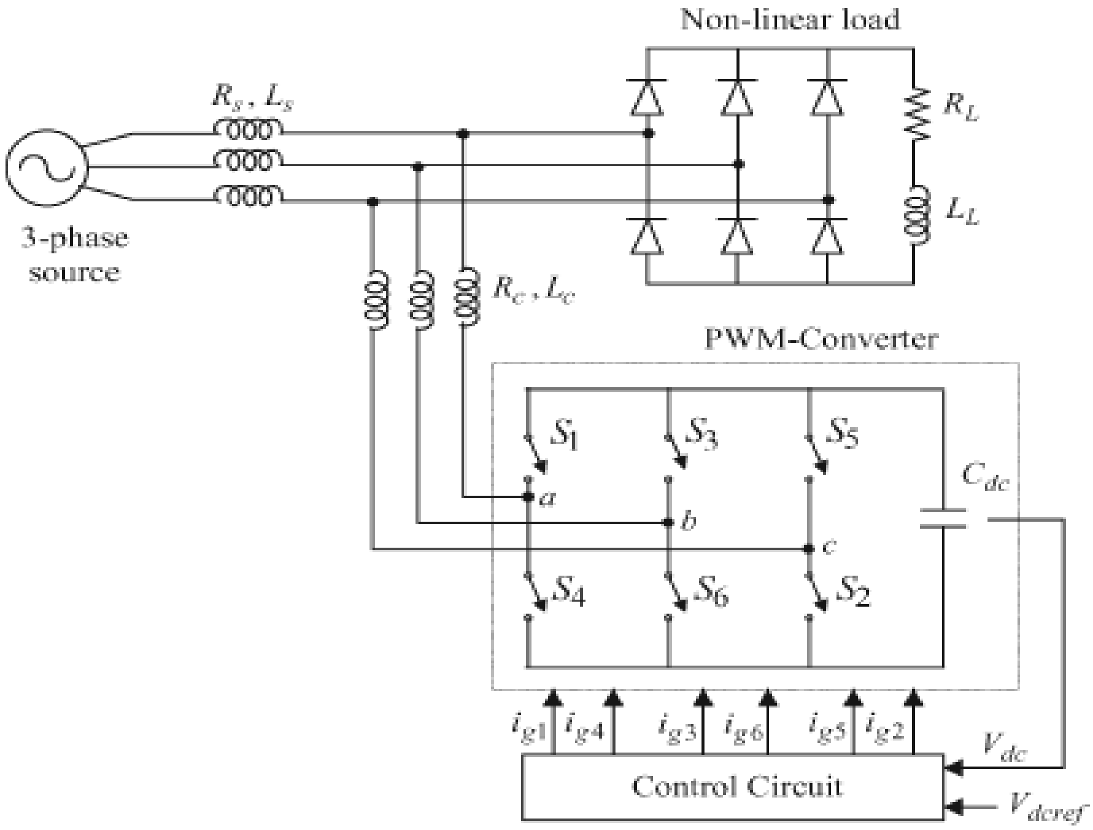

Figure.4.1.Schematic diagram of closed loop fuzzy logic controlled shunt active power filter.

The switching signals for the PWM converter are obtained by comparing the actual source currents (i_{sa}, i_{sb}, and i_{sc}) with the reference current templates (i_{sa}^*, i_{sb}^*, and i_{sc}^*) in the hysteresis current controller. Switching signals so obtained, after proper amplification and isolation, are given to switching devices of the PWM converter [6].

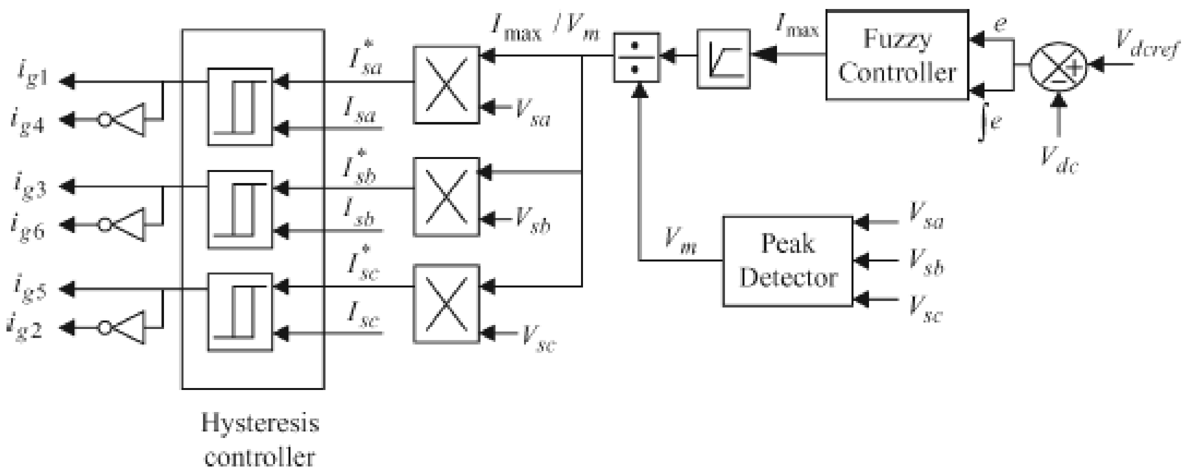

Figure.4.2.Fuzzy Control scheme

4.1. BASIC FUZZY ALGORITHM

In a fuzzy logic controller, the control action is determined from the evaluation of a set of simple linguistic rules. The development of the rules requires a thorough understanding of the process to be controlled, but it does not require a mathematical model of the system. The internal structure of the fuzzy controller is shown in Fig.4.2.

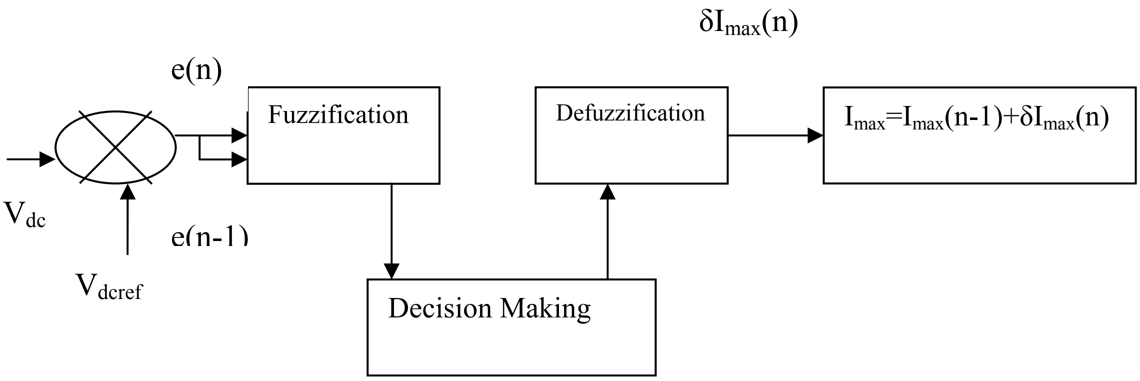

Figure 4.3. Internal structure of fuzzy logic controller.

A fuzzy inference system (or fuzzy system) basically consists of a formulation of the mapping from a given input set to an output set using fuzzy logic. This mapping process provides the basis from which the inference or conclusion can be made. A fuzzy inference process consists of the following steps:

- Step 1:Fuzzification of input variables

- Step 2: Application of fuzzy operator (AND,OR,NOT) in the IF(antecedent) part of the rule
- Step 3: Implication from the antecedent to the consequent(THEN part of the rules)
- Step 4: Aggregation of the consequents across the rules
- Step 5: Defuzzification

The crisp inputs are converted to linguistic variables in fuzzification based on membership function (MF). An MF is a curve that defines how the values of a fuzzy variable in a certain domain are mapped to a membership value μ (or degree of membership) between 0 and 1. A membership function can have different shapes, as shown in figure 4.4. The simplest and most commonly used MF is the triangular-type, which can be symmetrical or asymmetrical in shape. A trapezoidal MF has the shape of a truncated triangle. Two MFs are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian distribution curves. The bell MF with a flat top is somewhat different from a Gaussian function. Both Gaussian and bell MFs are smooth and non-zero at all points.

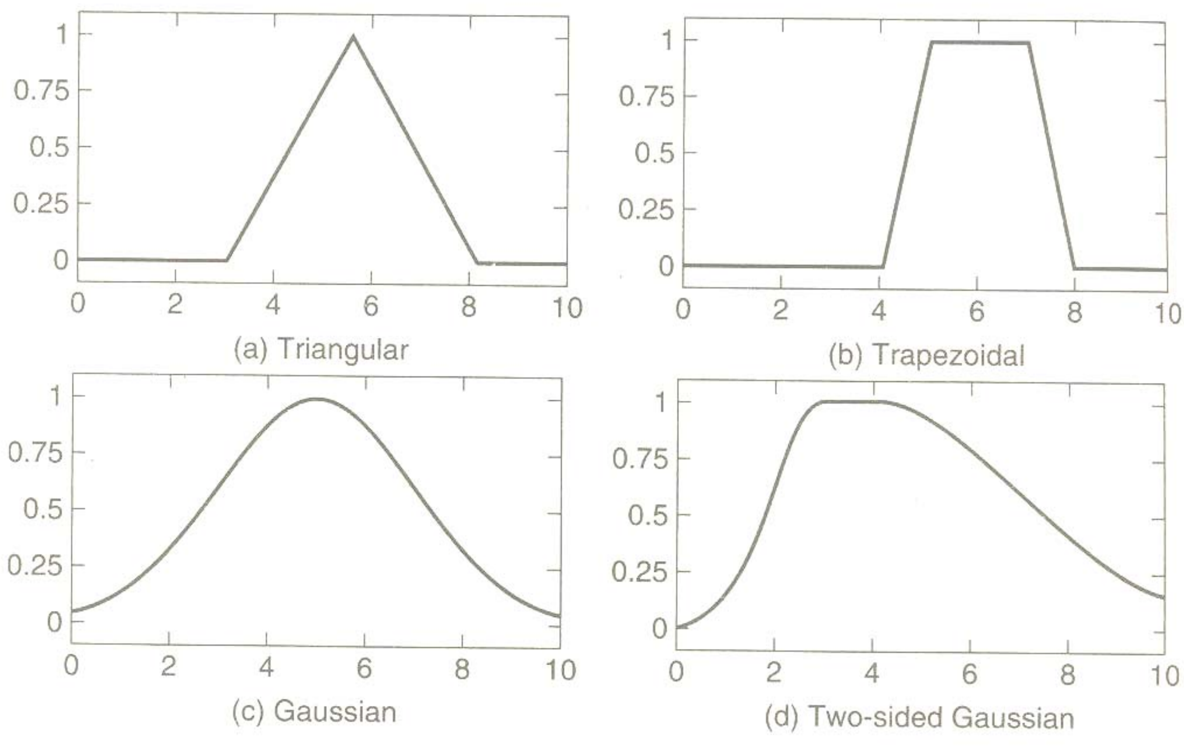

Figure.4.4. Different types of membership functions.

The basic properties of Boolean logic are also valid for Fuzzy logic. Once the inputs have been fuzzified, we know the degree to which each part of the antecedent of a rule has been satisfied. Based on the rule, OR or AND operation on the fuzzy variables is done.

The implication step helps to evaluate the consequent part of a rule. There are a number of implication methods in the literature, out of which Mamdani and TS types are frequently used. Mamdani, proposed this method which is the most commonly used implication method. In this, the output is truncated at the value based on degree of membership to give the fuzzy output. Takagai-Sugeno-Kang method of implication is different from Mamdani in a way that, the output MFs is only constants or have linear relations with the inputs.

The result of the implication and aggregation stpes is the fuzzy output which is the union of all the outputs of individual rules that are validated or “fired”. Conversion of this fuzzy output to crisp output is defines as defuzzification. There are many methods of defuzzification out of which Center of Area (COA) and Height method are frequently used. In the COA method (often called the center of gravity method) of defuzzification, the crisp output of particular variable Z is taken to be the geometric center of the output fuzzy value $\mu_{out}(Z)$ area, where this area is formed by taking the union of all contributions of rules whose degree of fulfillment is greater than zero. In height method of defuzzification, the COA method is simplified to consider the height of the each contributing MF at the mid-point of the base.

Here in this scheme, the error *e* and change of error *ce* are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) [6].

The fuzzy controller is characterized as follows:

- Seven fuzzy sets for each input and output.
- Triangular membership functions for simplicity.
- Fuzzification using continuous universe of discourse.
- Implication using Mamdani's 'min' operator.
- Defuzzification using the 'height' method.

Figure. 4.5. shows the normalized triangular membership functions used in fuzzification.

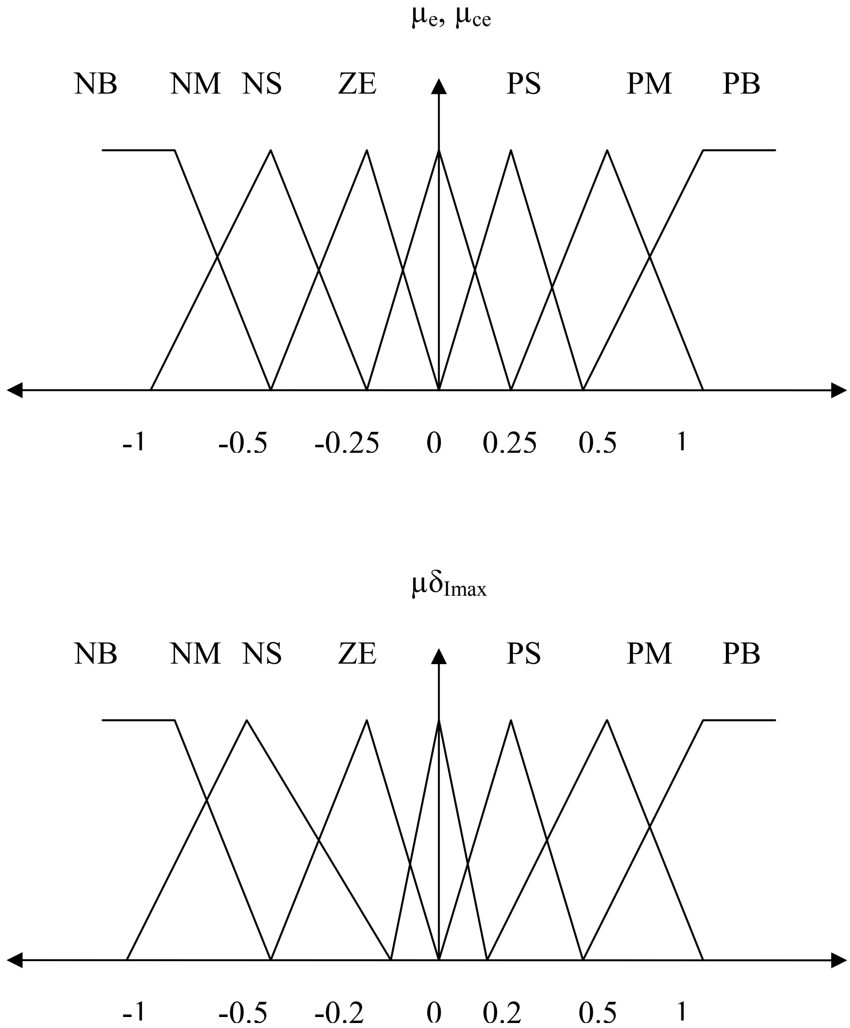

Figure.4.5. Normalized triangular functions used in fuzzification
(a)Membership functions for *e* and *ce*
(b)Membership function for δI_{max}

4.2. DESIGN OF CONTROL RULES

The fuzzy control rule design involves defining rules that relate the input variables to the output model properties. As FLC is independent of the system model, the design is mainly based on the intuitive feeling for, and experience of, the process. A new methodology for rule base design based on the general dynamic behavior of the process has been introduced in [18] which is further modified [14].

The input variables of the FLC are the error *e* and the change of error *ce*. The output is the change of the reference current (δI_{max}). The time step response of a stable closed loop system should have a shape shown in figure 4.6. and figure 4.7. shows the phase plane trajectory of the step response, which shows the mapping of the error against the change in error.

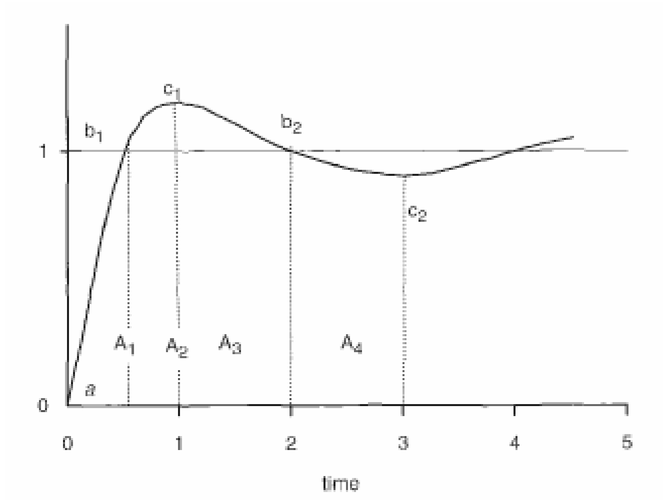

Figure.4.6. Time step response of a stable closed loop system.

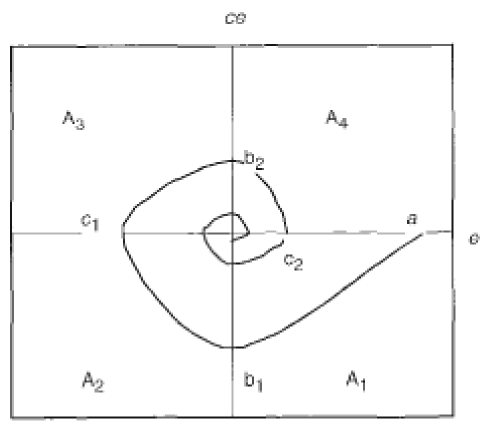

Figure.4.7. Phase plane trajectory of step response.

The system equilibrium point is the origin of the phase plane. The time response has been divided into four regions A_1,A_2,A_3, and A_4 and two sets of points - cross-over (b_1, b_2) and peak (c_1, c_2). The index used for identifying the response area is defined as

A_1: if e>0&ce<0, A_2: if e<0&ce<0

A_3:if e<0&ce>0, A_4: if e>0&ce>0

The cross over index:

b_1 : e>0 to e<0,ce<0

b_2 : e<0 to e>0,ce>0

and the peak valley index:

c_1: ce=0,e<0, and c_2: ce=0,e>0

Based on these four areas, two sets of points and phase plane trajectory of *e* and ce, the rule base is framed. The corresponding rule for the region 1 can be formulated as rule R_1 and has the effect of shortening the rise time

R_1 : if *e* is + ve and *ce* is - ve, then δI_{max} is +ve

Rule 2 for region 2 decreases the overshoot of the system response, which can be written as

R_2 : if *e* is - ve and *ce* is - ve; then δI_{max} is – ve

Similarly, rules for other regions can be formed. For are determined based on the theory that in the transient better control performance finer fuzzy partitioned sub- state, large errors need coarse control, which requires spaces (NB, NM, NS, ZE, PS, PM, PB) are used, and coarse input/output variables; in the steady state, are summarized in Table 4.2.1. The elements of this table however, small errors need fine control, which requires fine input/output variables. Based on this, the elements of the rule table are obtained from an understanding of the filter behavior and modified by simulation performance.

error(e) b1

A_2

A_1

c1

Change in error(ce)

a,c_2

	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	Ps
NB	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

A_3

A_4

b2

Table.4.1.Control rule table

Chapter 5

MODELING OF THE SYSTEM

Modeling of nonlinear load

Modeling of PWM converter

Estimation of peak supply current

Estimation of instantaneous reference supply currents

Hysteresis current controller

A program is developed to simulate the fuzzy logic based shunt active power filter in MATLAB. The complete active power filter system is composed mainly of three-phase source, a nonlinear load, a voltage source PWM converter, and a fuzzy controller or a PI controller. All these components are modeled separately, integrated and then solved to simulate the system.

5.1. MODELING OF NONLINEAR LOAD

A three-phase diode rectifier with input impedance and R-L load is considered as a nonlinear load. Due to the presence of source inductance, six overlapping and six non-overlapping conduction intervals occur in a cycle. During a non-overlapping interval only two devices will conduct while during an overlapping interval three devices of the bridge will conduct simultaneously. The dynamic equations during non-overlap and overlap intervals are given in (1) and (2) respectively:

$$pi_d = (V_o - (2R_s + R_L)i_d - 2v_d)/(2L_s + L) \tag{5.1.1}$$

$$pi_d = (V_o - (1.5R_s + R_L)i_d - 2v_d)/(1.5L_s + L) \tag{5.1.2}$$

Where R_s and L_s are the elements of the source inductance, v_d is the voltage drop across each device, R_L and L are the elements of load impedance, i_d is the load current flowing through the diode pairs and ***p*** is the differential operator d/dt). V_0 is the AC side line voltage segment (v_{ac}, v_{bc}, v_{ba}, v_{ca}, v_{cb}, v_{ab} during non-overlap, and $v_{bc}+v_{ac}/2$, $v_{ba}+v_{bc}/2$, $v_{ca}+v_{ba}/2$, $v_{cb}+v_{ca}/2$, $v_{ab}+v_{cb}/2$, $v_{ac}+v_{ab}/2$ during overlap intervals) based on diode pair conduction. The phase currents i_{sa}, i_{sb}, and i_{sc} are obtained by i_d, considering the respective diode pair conduction.

5.2. MODELING OF PWM CONVERTER

The PWM converter has been modeled as having a three phase AC voltage applied through a filter impedance (R_c ,L_c) on its input, and DC bus capacitor on its output. The three phase voltages v_{fa}, v_{fb}, and v_{fc} reflected on the input side can be expressed in terms of the DC bus capacitor voltage V_{dc} and switching functions stating the on/off status of the devices of each leg S_a, S_b, and S_c as

$$\begin{aligned} v_{fa} &= (V_{dc}/3)(2S_a - S_b - S_c) \\ v_{fb} &= (V_{dc}/3)(-S_a + 2S_b - S_c) \\ v_{fc} &= (V_{dc}/3)(-S_a - S_b + 2S_c) \end{aligned} \tag{5.2.1}$$

The three phase currents i_{fa}, i_{fb}, and i_{fc} flowing through impedances ($R_{c,}$ L_c) are obtained by solving the following differential equations:

$$
\begin{aligned}
p_{ifa} &= (1/L_c)(R_c i_{fa} + (v_{sa} - v_{fa}) \\
p_{ifb} &= (1/L_c)(R_c i_{fb} + (v_{sb} - v_{fb}) \\
p_{ifc} &= (1/L_c)(R_c i_{fc} + (v_{sc} - v_{fc})
\end{aligned}
\qquad (5.2.2)
$$

The DC capacitor current can be obtained in terms of phase currents i_{fa}, i_{fb}, and i_{fc} and the switching status (1 for on and 0 for off) of the devices $S_{a,}$ S_b and S_c

$$i_{dc} = i_{fa} S_a + i_{fb} S_b + i_{fc} S_c \qquad (5.2.3)$$

From this, the model equation of the DC side capacitor voltage can be written as

$$pV_{dc} = (1 / C_{dc})(i_{fa} S_a + i_{fb} S_b + i_{fc} S_c) \qquad (5.2.4)$$

5.3. ESTIMATION OF PEAK SUPPLY CURRENT

Peak value of the supply current (I_{max}) is estimated using PI controller and fuzzy controller over the voltage of the APF dc bus. The DC voltage is sensed at every one sixth period of AC source frequency. The dc bus voltage ($V_{dc}(n)$) is compared with its reference value (V_{dcref}). The resulting voltage error $V_e(n)$ at n^{th} sampling instant is expressed as

$$V_e(n) = V_{dcref} - V_{dc}(n) \qquad (5.3.1)$$

The output of PI controller $V_0(n)$ at the n^{th} sampling instant is expressed as:

$$V_0(n) = V_0(n-1) + K_p\{V_e(n) - V_e(n-1)\} + K_i V_e(n) \qquad (5.3.2)$$

Where K_p and K_i are proportional and integral gain constants of the voltage controller. V_0(n-1) and V_e(n-1) are the output voltage controller and voltage error at (n-1)th sampling instant. This output $V_0(n)$ of the voltage controller is taken as peak value of source current (I_{max}).

The peak value of the reference current I_{max} is estimated using fuzzy controller by controlling the DC side capacitor voltage in closed loop. The output of fuzzy control algorithm is change in peak current $\delta I_{max}(n)$. The peak reference current $I_{max}(n)$, at the n^{th} sampling instant is determined by adding te previous peak current $I_{max}(n-1)$ to the calculated change in reference current:

$$I_{max}(n) = I_{max}(n-1) + \delta I_{max}(n-1) \qquad (5.3.3)$$

In classical control theory this is integrating effect, which increases the system type and improves steady state error.

5.4. ESTIMATION OF INSTANATANEOUS REFERENCE SUPPLY CURRENTS

Harmonic free unity power factor, three-phase supply currents can be estimated using unit current templates in phase with the supply voltages and their peak values. The unit current templates are derived as

$$u_{sa} = v_{sa} / V_{sm} \quad ;$$
$$u_{sb} = v_{sb} / V_{sm} \quad ; \qquad (5.4.1)$$
$$u_{sc} = v_{sc} / V_{sm} \; .$$

The three-phase supply voltages are expressed as

$$v_{sa} = v_{sm} \sin \omega t \; ;$$
$$v_{sb} = v_{sm} \sin \omega t \; ; \qquad (5.4.2)$$
$$v_{sc} = v_{sm} \sin \omega t \; .$$

Where V_{sm} is the peak value of source voltage and ω is the supply frequency. The instantaneous reference supply currents are compared as

$$i_{sa}^{*} = I_{\max} u_{sa}$$
$$i_{sb}^{*} = I_{\max} u_{sb} \qquad (5.4.3)$$
$$i_{sc}^{*} = I_{\max} u_{sc}$$

5.5. HYSTERESIS CURRENT CONTROLLER

The current controller decides the switching patterns of the devices in the APF. The switching logic is formulated as

if $i_{sa} < (i_{sa}^{*}$ - hb) upper switch is OFF and lower switch is ON in leg “a” of the APF;

if $i_{sa} > (i_{sa}^{*}$ - hb) upper switch is ON and lower switch is OFF in leg “a” of the APF.

Similarly, the switches in the legs “b” and “c” are activated. Here, hb is the width of the hysteresis band around which the reference currents. In this fashion, the supply currents are regulated within the hysteresis band of their respective reference values.

The performance of active filter is analyzed by solving set of differential equations (5.1.1)-(5.4.3), with other expressions by a fourth order Runga kutta method.

Chapter 6

SIMULATION RESULTS

A program is developed to simulate the both PI controller based and fuzzy logic based shunt active power filter in MATLAB. The complete active power filter system is composed mainly of three-phase source, a nonlinear load, a voltage source PWM converter, and a fuzzy controller or a PI controller. All these components are modeled separately, integrated and then solved to simulate the system.

Figures 6.1.- 6.8 show the simulations results of the proposed shunt active power filter controlled by fuzzy logic and a conventional PI controller with MATLAB program. The parameters selected for simulation studies are given in table 6.1. The three phase source voltages are assumed to be balanced and sinusoidal. The source voltage waveform of the reference phase only (phase-a, in this case) is shown in fig.6.1.

A load with highly nonlinear characteristics is considered for the load compensation. The THD in the load current is 28.05%. The phase-a load current is shown in figure 6.2. The source current is equal to the load current when the compensator is not connected.

System Parameters	Values
Source voltage(V_s)	100V(peak)
System frequency(f)	50Hz
Source impedance(R_s,L_s)	0.1Ω;0.15mH
Filter impedance(R_c,L_c)	0.4Ω;3.35mH
Load impedance(R_l,L_l)	6.7Ω;20mH
DC link capacitance	2000μF
Reference DClink voltage(V_{dcref})	220V

Table6.1.System parameters for simulation study.

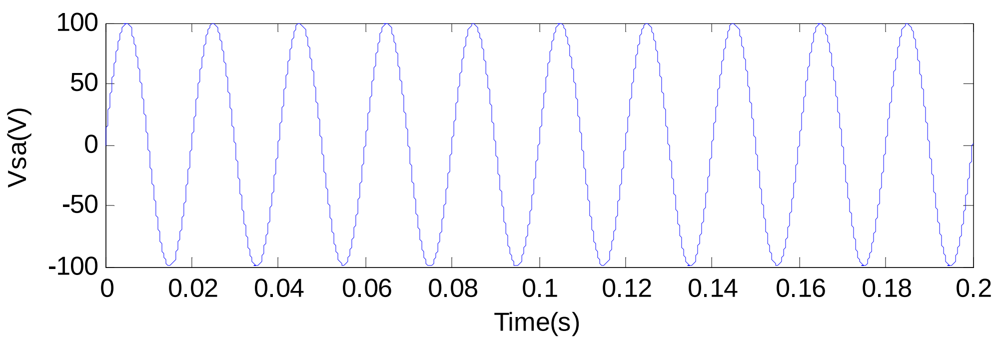

Figure.6.1. Source voltage.

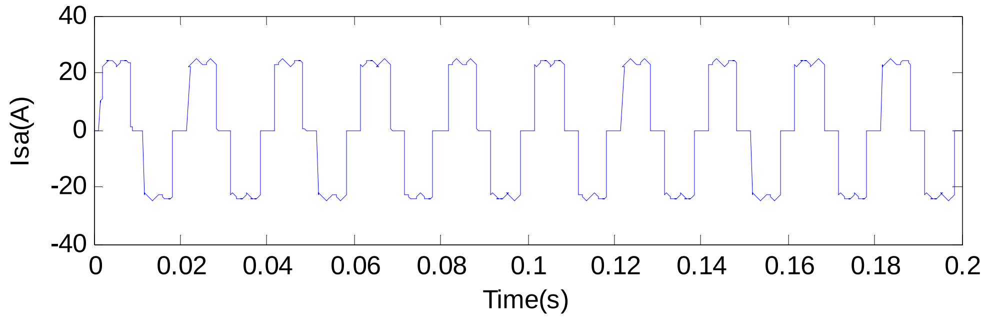

Figure.6.2. Source current when the compensator is not connected.

The compensator is switched ON at t=0.05s and the integral time square error (ITSE) performance index is used for optimizing the and coefficients of the PI controller. The optimum values (K_p and K_i) are found to be 0.2 and 9.32, respectively, which corresponds to the minimum value of ITSE. The source currents for PI and fuzzy controllers are shown in Figs.6.3 and 6.6, respectively. Compensating currents of PI and fuzzy controllers are shown in figures 6.4 and 6.7. The DC side capacitor voltage during switch on response is shown in figures 6.5. and 6.8 of PI and fuzzy controllers.

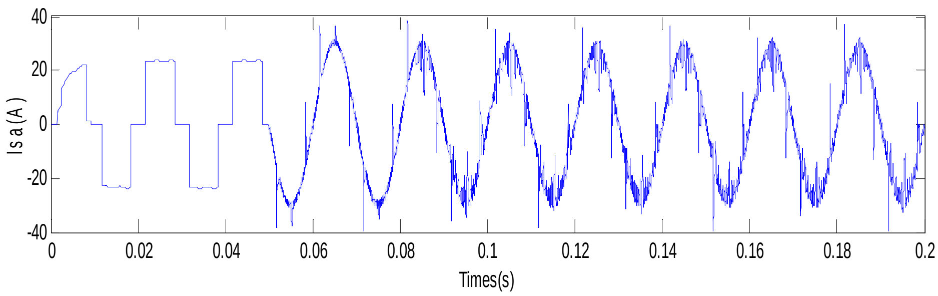

Figure.6.3. Source current PI controller.

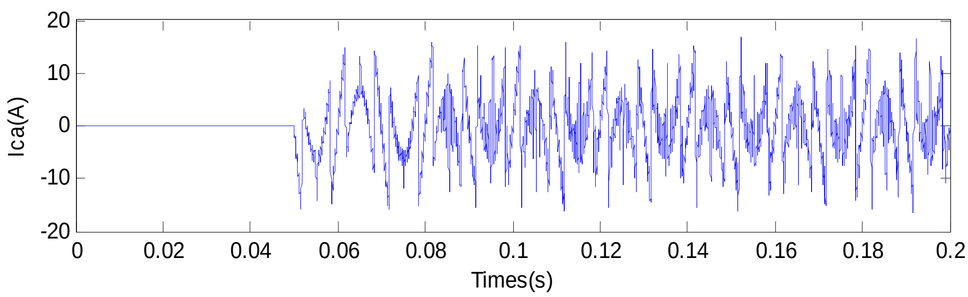

Figure.6.4. Compensating current of PI controller.

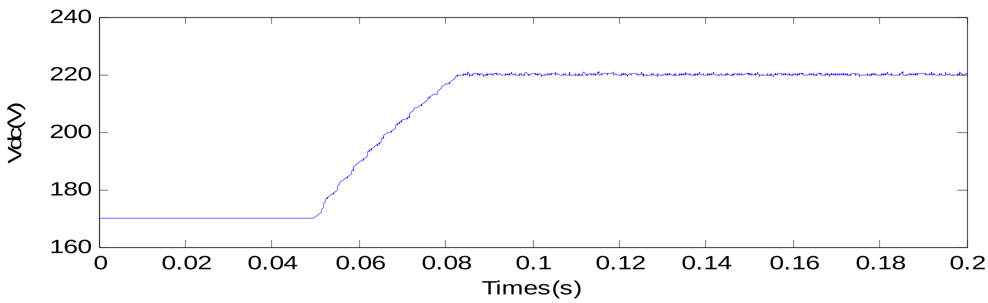

Figure.6.5.DC Capacitor voltage during switch-on response with PI controller.

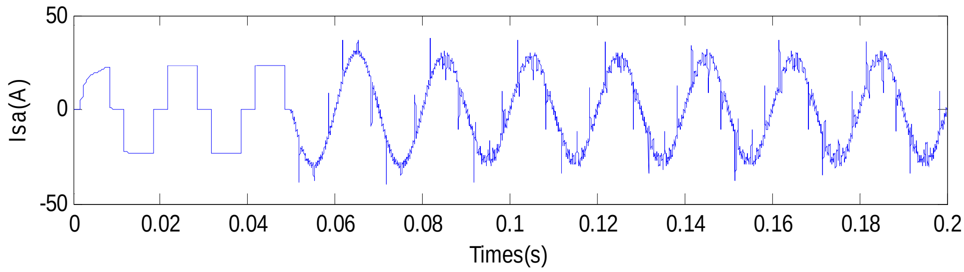

Figure.6.6.Source current fuzzy controller.

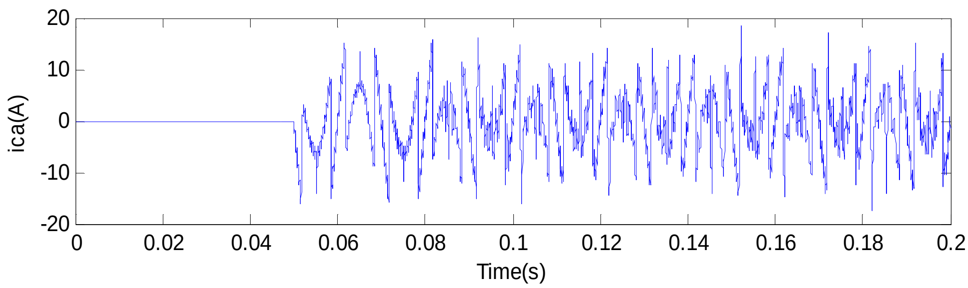

Figure.6.7. Compensating current of fuzzy controller.

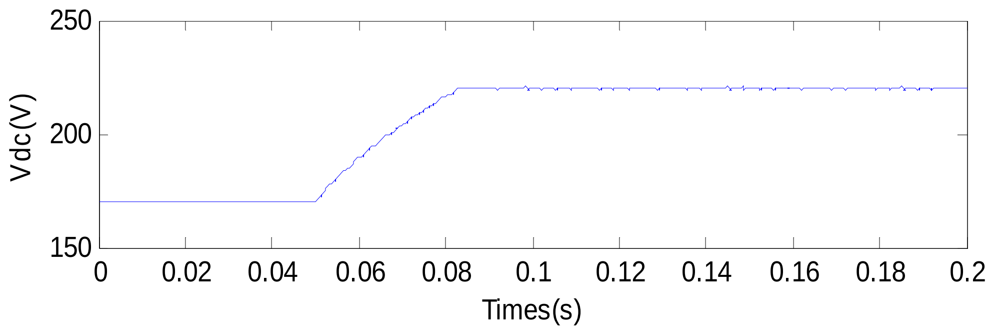

Figure.6.8. DC Capacitor voltage during switch-on response with Fuzzy controller

From the wave forms it is clear that harmonic distortion is reduced after connecting compensator. Compared to PI controller fuzzy controller fuzzy controller gives better harmonic compensation.

The system studied has also been modeled using simulink and performance of PI and Fuzzy controllers is analyzed. The system parameters selected for simulation study are given in table 6.1 and 6.2. Figures 6.9-6.18 shows the simulation results of the implemented system with PI controller and fuzzy controllers with simulation parameters mentioned in table 6.1. The source voltage waveform of the reference phase only (phase-a, in this case) is shown in fig.6.9. A diode rectifier with R-L load is taken as non-linear load. The THD of the load current is 27.88%. The optimum values (K_p and K_i) are found to be 0.2 and 9.32 respectively.

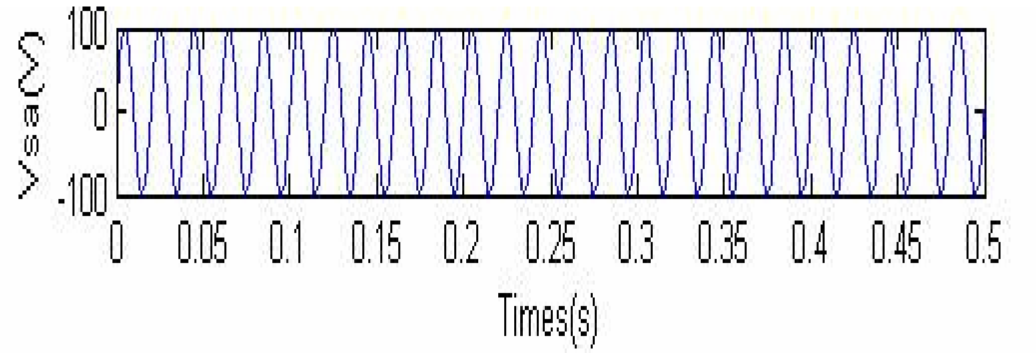

Figure.6.9. Source voltage.

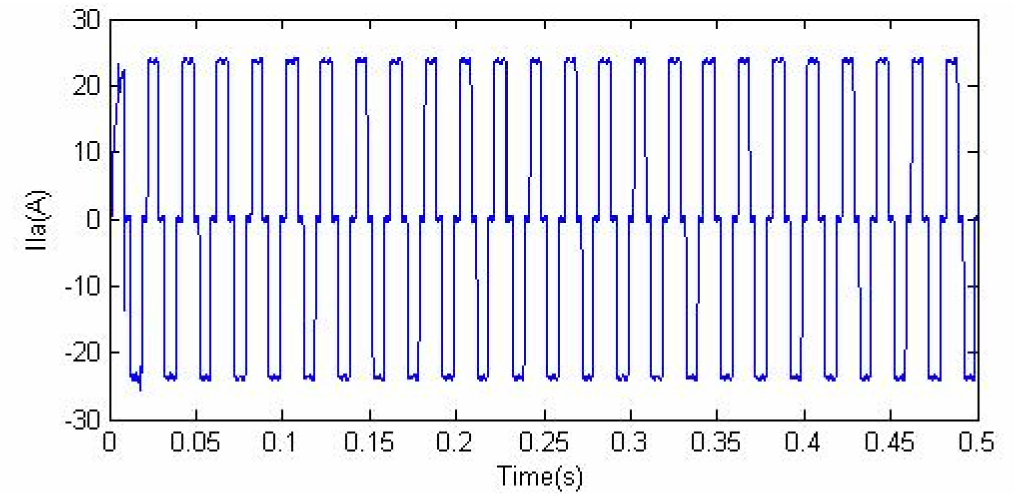

Figure.6.10.Load current.

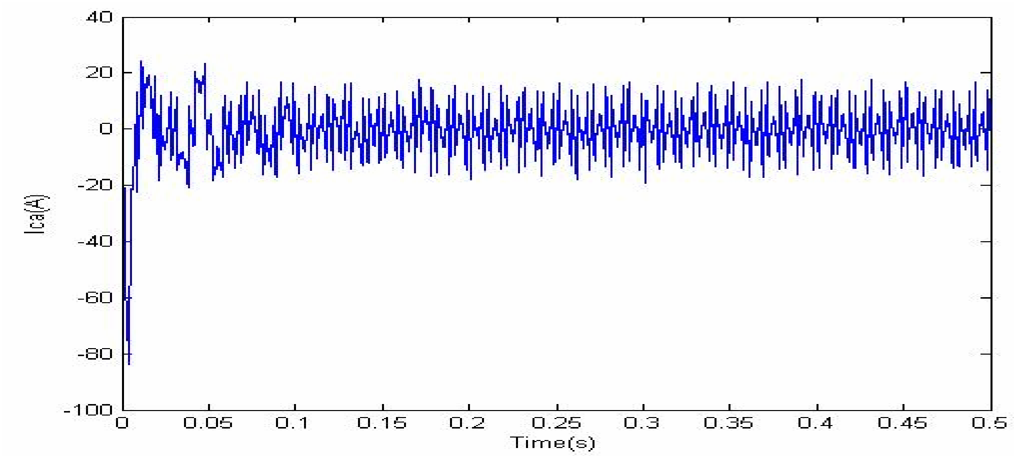

Figure.6.11. Compensating current with PI controller.

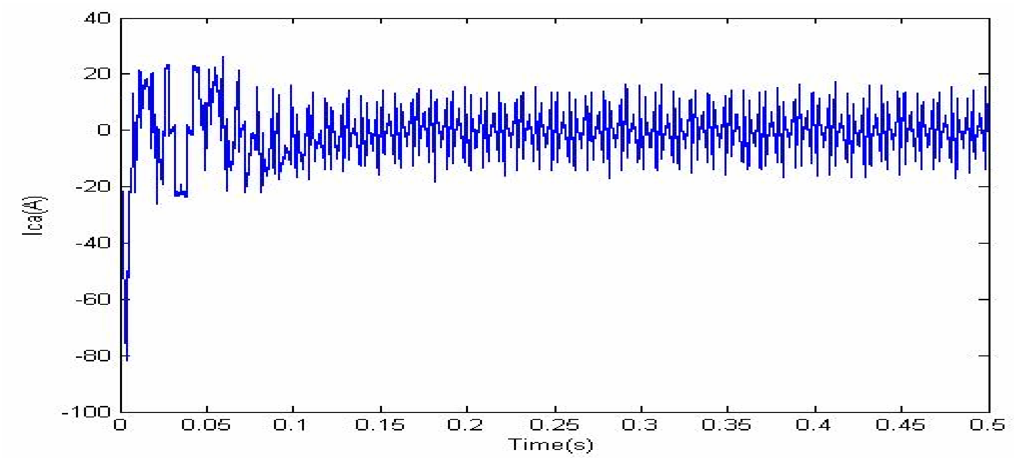

Figure.6.12. Compensating current with fuzzy controller.

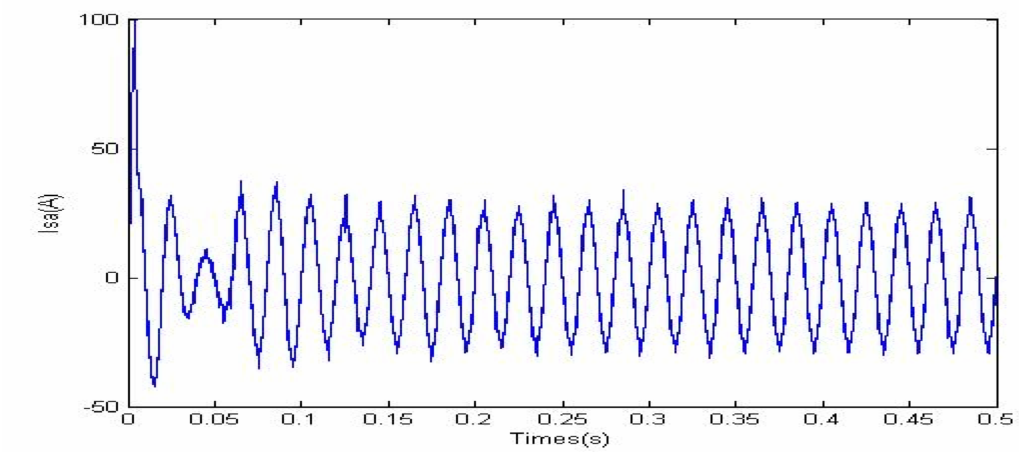

Figure.6.13. Source current with PI controller.

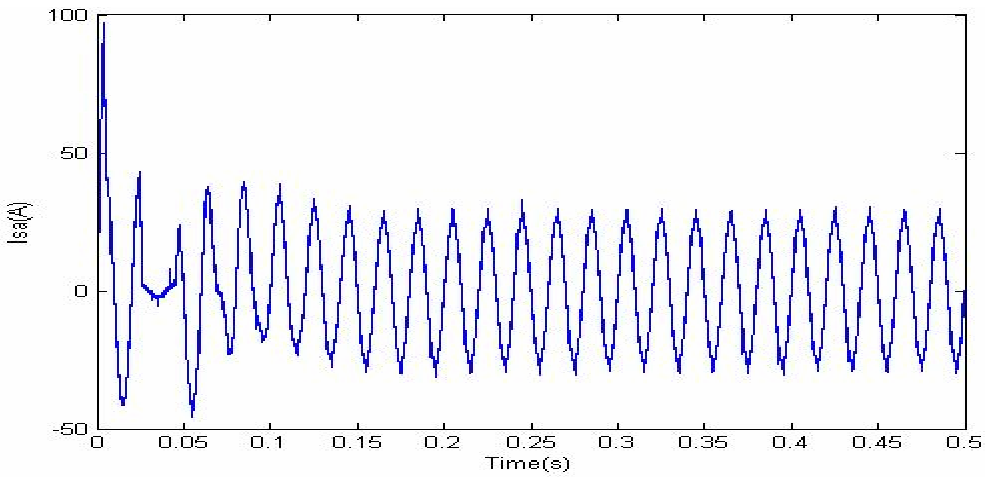

Figure.6.14. Source current with fuzzy controller.

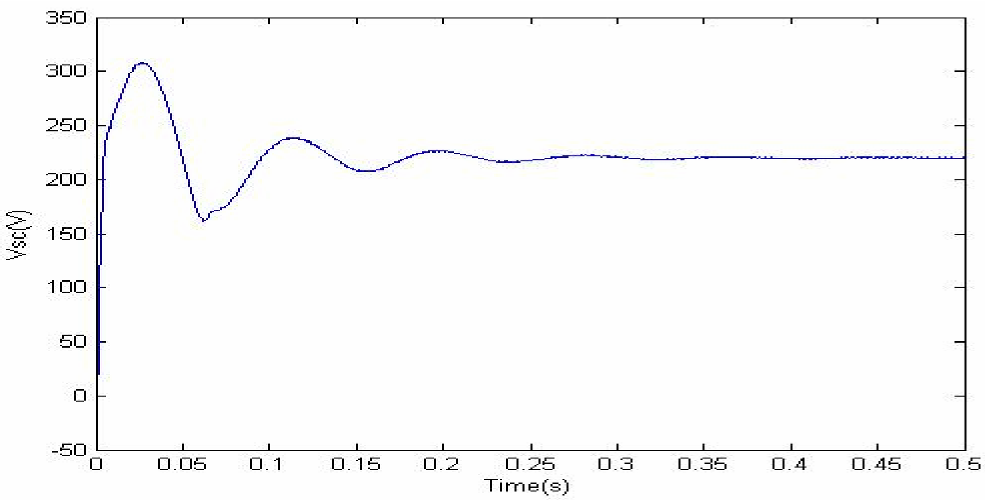

Figure.6.15. DC side capacitor voltage with PI controller.

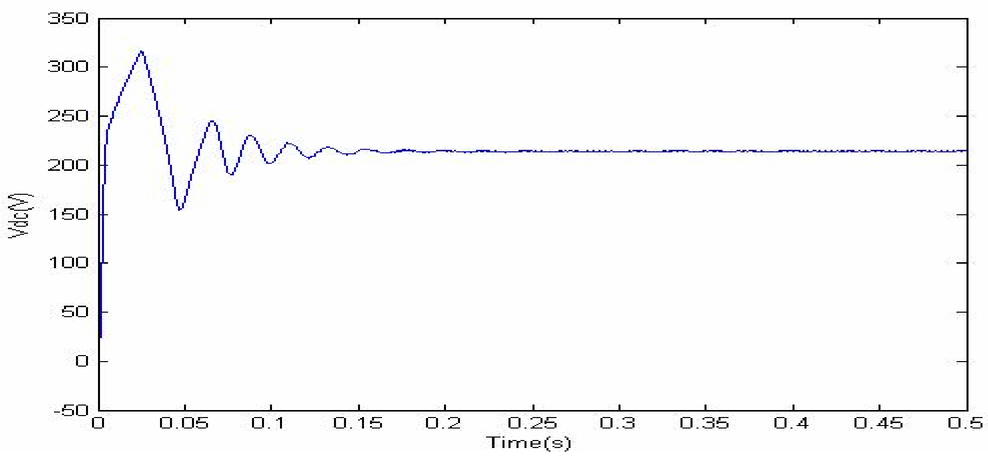

Figure.6.16. DC side capacitor voltage with PI controller.

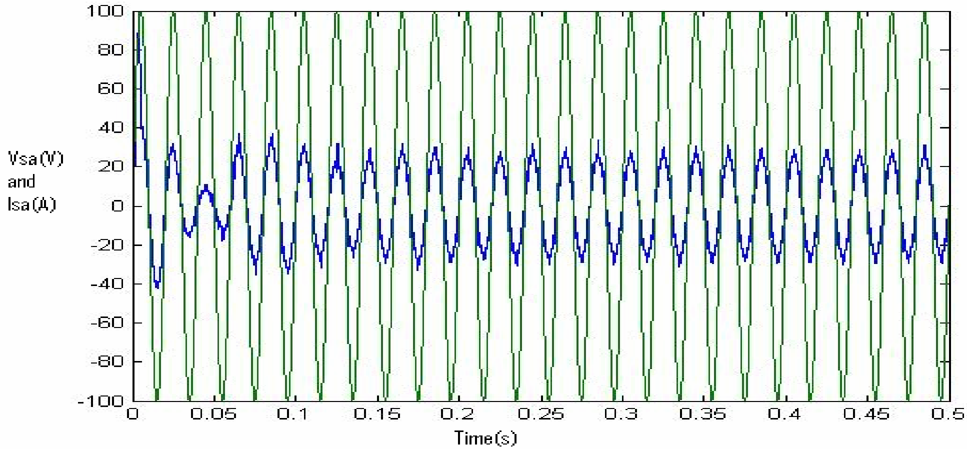

Figure.6.17. Voltage and current in phase with PI controller after compensation.

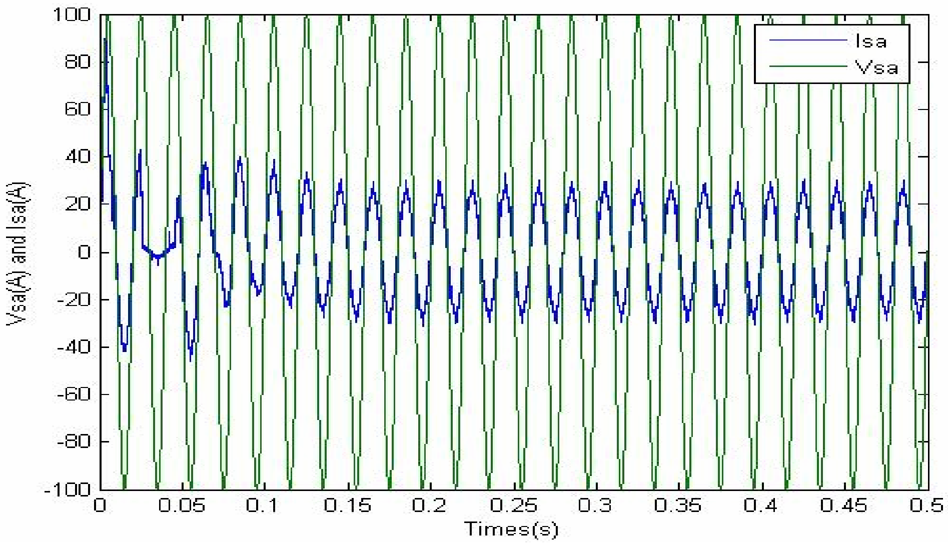

Figure.6.18. Voltage and current in phase with fuzzy controller after compensation.

From the responses it is depicted that the settling time required by the PI controller is approximately 8 cycles whereas incase of fuzzy controller is about 6 cycles. The source current THD is reduced form 27.88% to 2% incase of PI controller and 2.89% incase of fuzzy controller which is below IEEE standard with both the controllers.

Figures 6.19-6.28 shows the simulation results of the implemented system with PI controller and fuzzy controllers with simulation parameters mentioned in table 6.2. The source voltage waveform of the reference phase only (phase-a, in this case) is shown in fig.6.19. A diode rectifier with R-L load is taken as non-linear load. The THD of the load current is 28.34%.

System parameters	Values
Source voltage(V_s)	325V(peak)
System frequency(f)	50Hz
Source impedance(R_s,L_s)	0.1Ω,0.15mH
Filter impedance(R_c,L_c)	0.4Ω,3.35mH
Load impedance(R_l,L_l)	20Ω,20mH
Reference DClink voltage(V_{dcref})	680V
DC link capacitance	2000μF

Table.6.1.System parameters used in simulink.

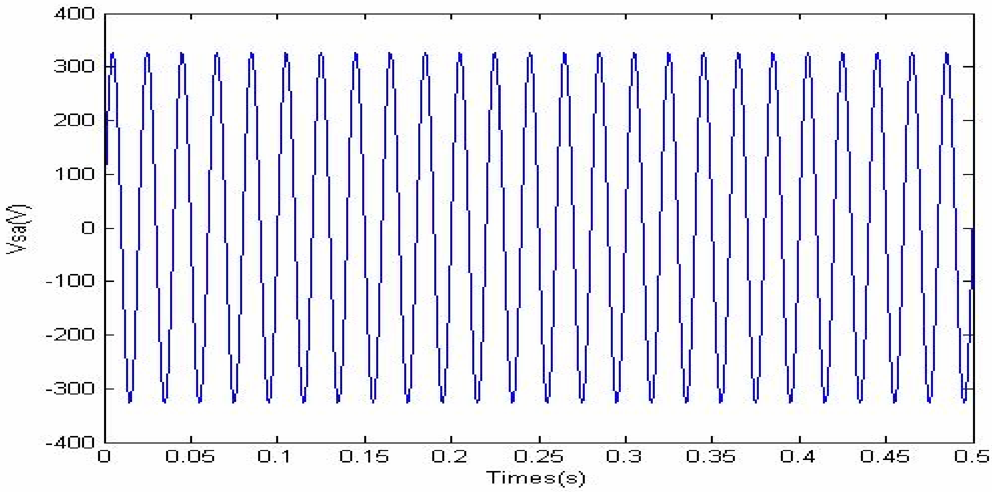

Figure.6.19. Source voltage.

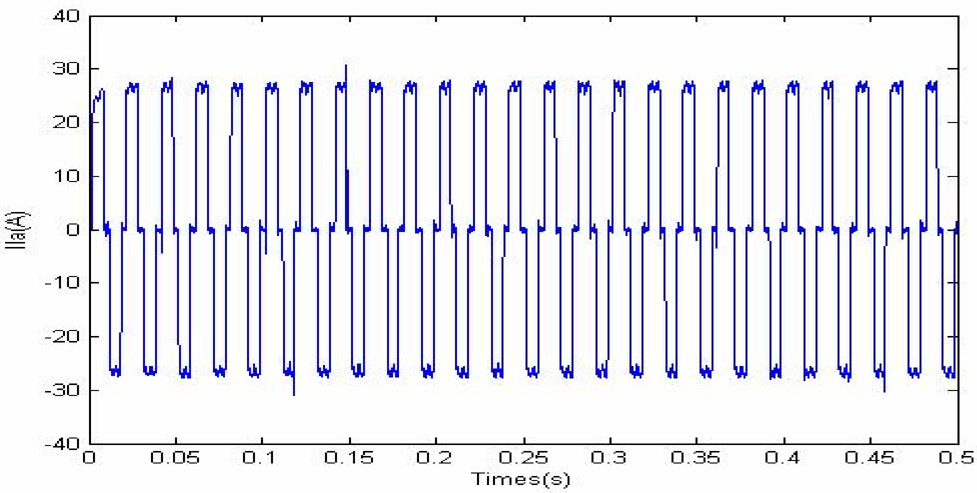

Figure.6.20.Load current.

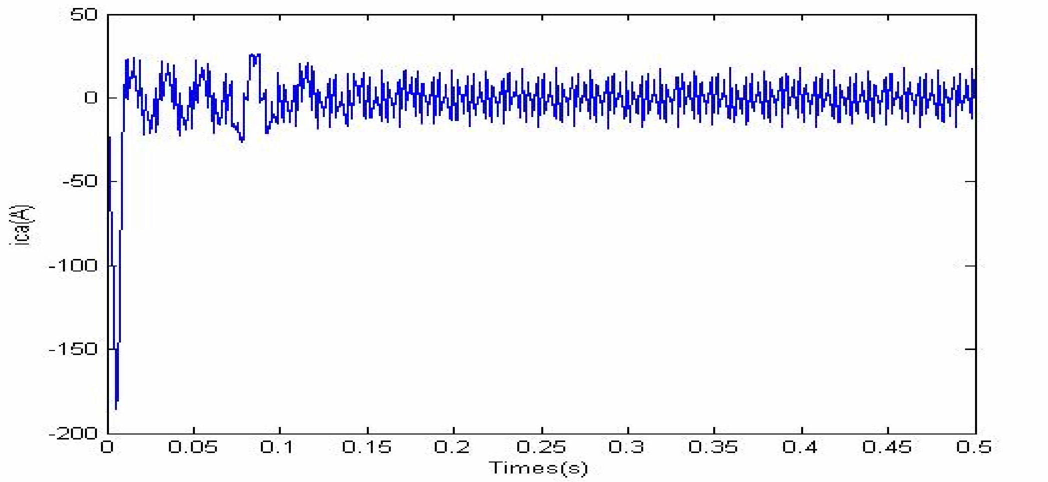

Figure.6.21. Compensating current with PI controller.

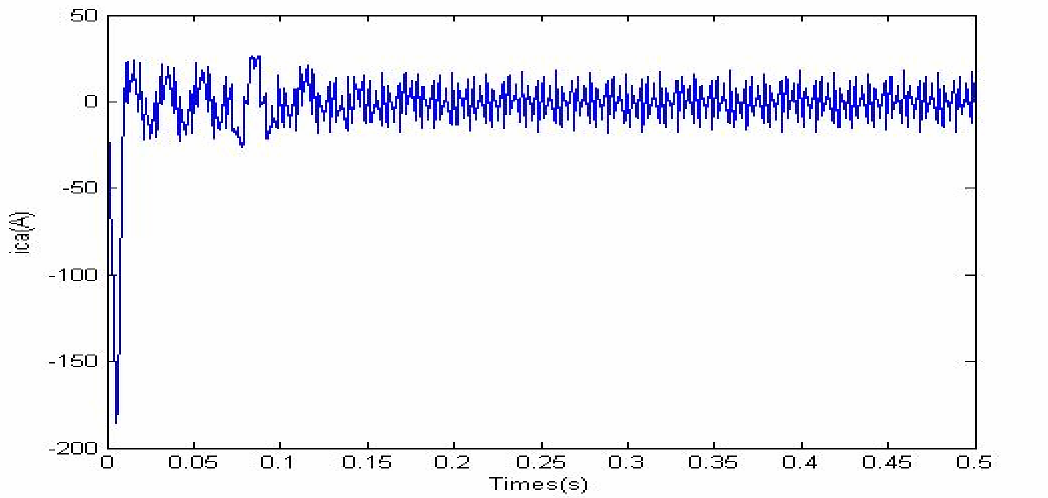

Figure.6.22. Compensating current with Fuzzy controller.

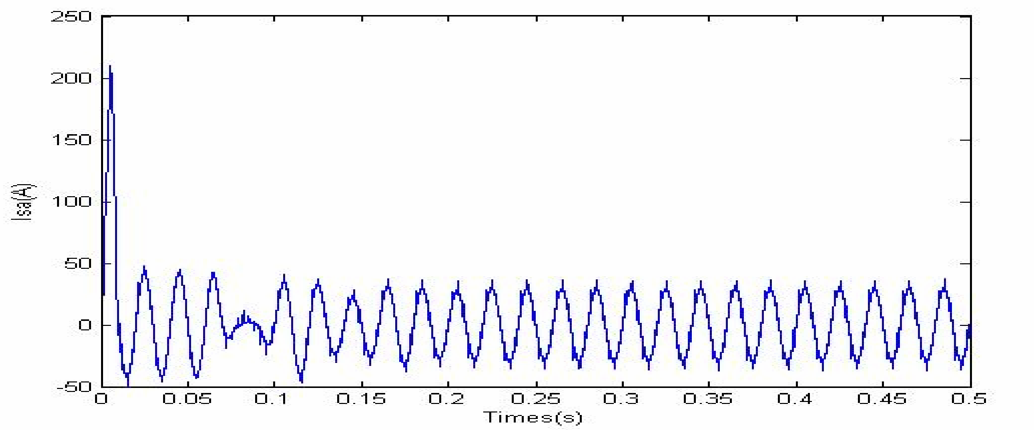

Figure.6.23. Source current with PI controller.

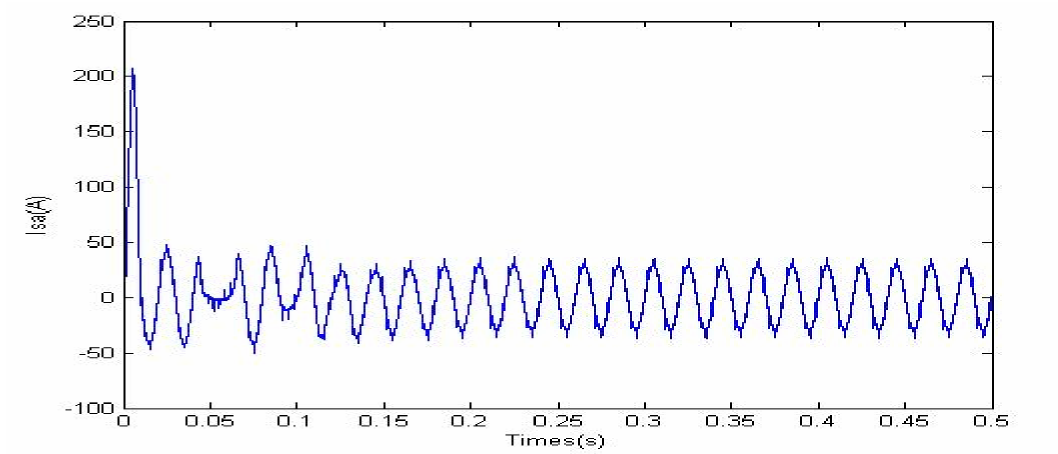

Figure.6.24. Source current with PI controller.

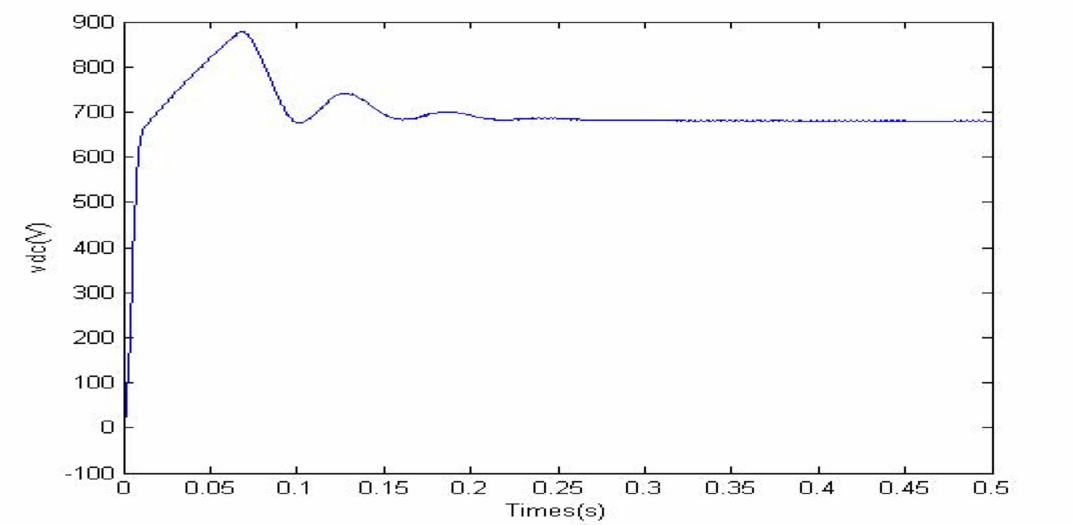

Figure.6.25. DC side capacitor voltage with PI controller.

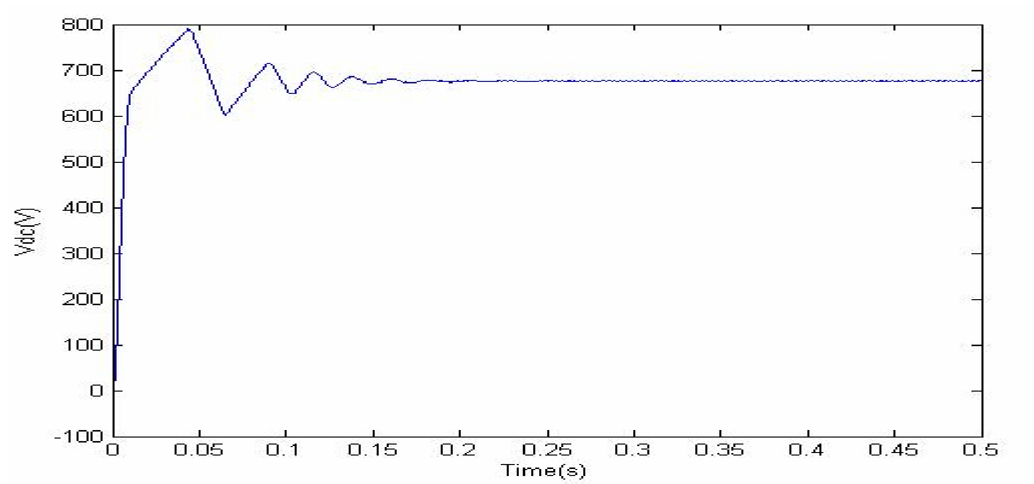

Figure.6.26. DC side capacitor voltage with Fuzzy controller.

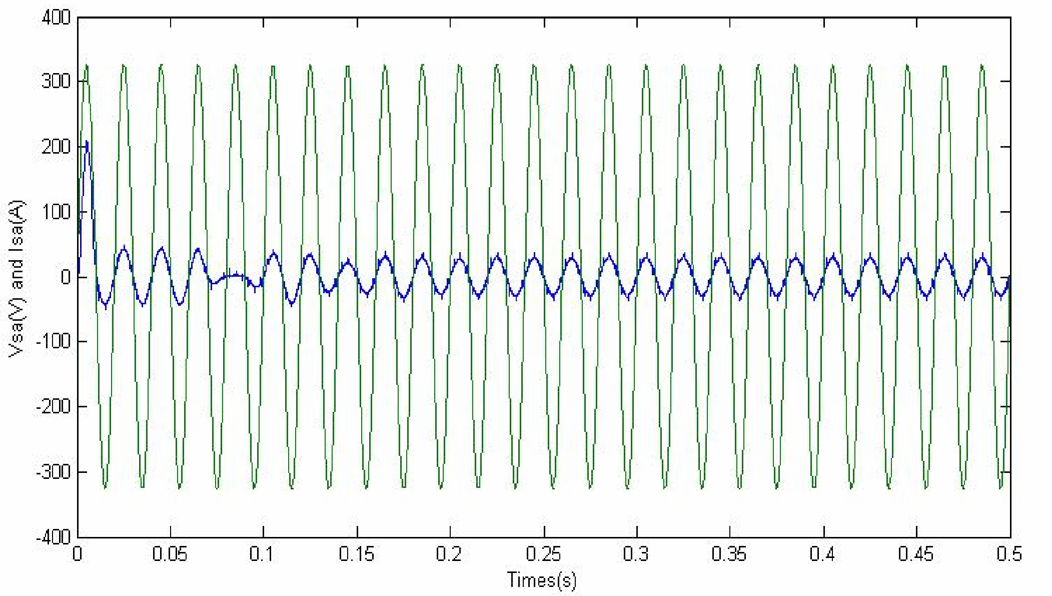

Figure.6.27. Voltage and current in phase with PI controller after compensation.

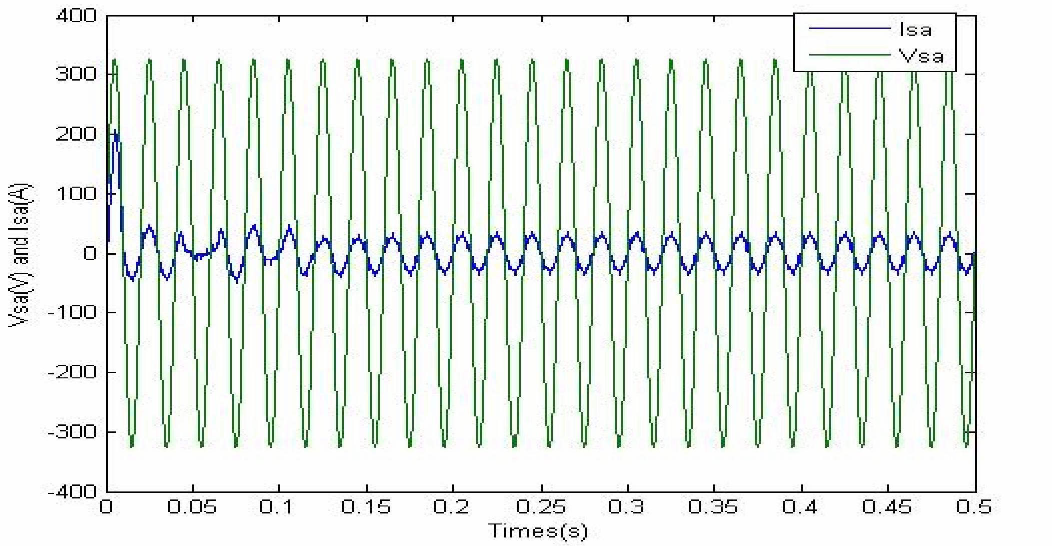

Figure.6.28. Voltage and current in phase with Fuzzy controller after compensation.

From the responses it is depicted that the settling time required by the PI controller is approximately 10 cycles whereas incase of fuzzy controller is about 7.5 cycles. The peak overshoot voltage incase of PI controller is 880Volts (approx) whereas incase of fuzzy controller is 780volts (approx). The source current THD is reduced form 28.34% to 4.7% which is below IEEE standard with both the controllers. After compensation both source voltage and current are in phase with each other means that the harmonics are eliminated and reactive power is compensated to make power factor close to unity. As the source current is becoming sinusoidal after compensation power quality is improved.

Chapter 7

CONCLUSION AND SCOPE FOR THE FUTURE WORK

CONCLUSION

A shunt active power filter has been investigated for power quality improvement. Various simulations are carried out to analyze the performance of the system. Both PI controller based and fuzzy logic controller based Shunt active power filter are implemented for harmonic and reactive power compensation of the non-linear load. A program has been developed to simulate the fuzzy logic based and PI controller based shunt active power filter in MATLAB. It is found from simulation results that shunt active power filter improves power quality of the power system by eliminating harmonics and reactive current of the load current, which makes the load current sinusoidal and in phase with the source voltage. The performance of both the controllers has been studied and compared. A model has been developed in MATLAB SIMULINK and simulated to verify the results. The fuzzy controller based shunt active power filter has a comparable performance to the PI controller in steady state except that settling time is very less in case of fuzzy controller. The THD of the source current is below 5%, the harmonics limit imposed by IEEE standard.

SCOPE FOR THE FUTURE WORK

Experimental investigations can be done on shunt active power filter by developing a prototype model in the laboratory to verify the simulation results for both PI and fuzzy controllers.

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APPENDIX-A

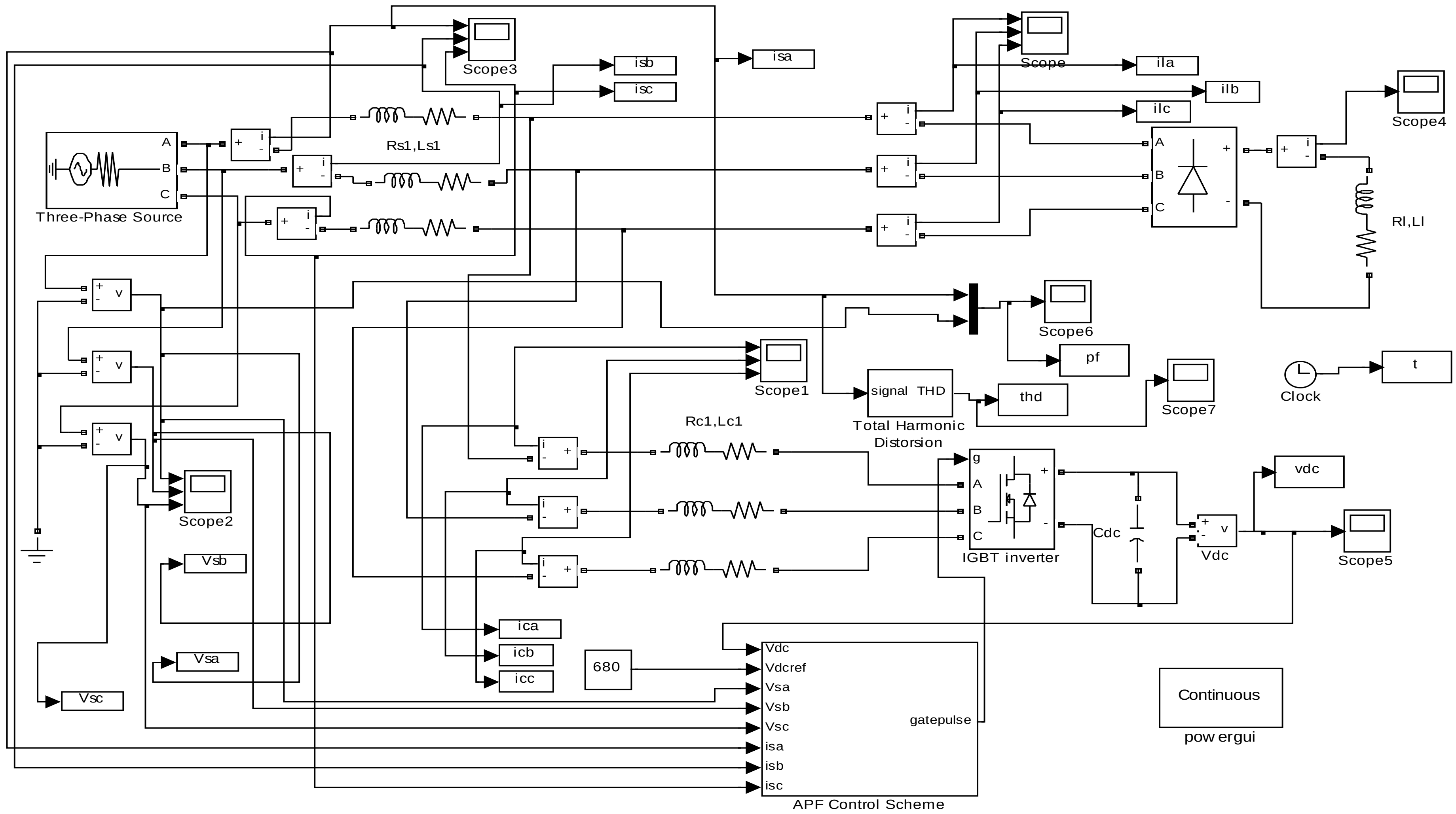

FIGURE 1. MATLAB SIMULINK MODEL FOR SHUNT ACTIVE POWER FILTER SIMULATION STUDY.

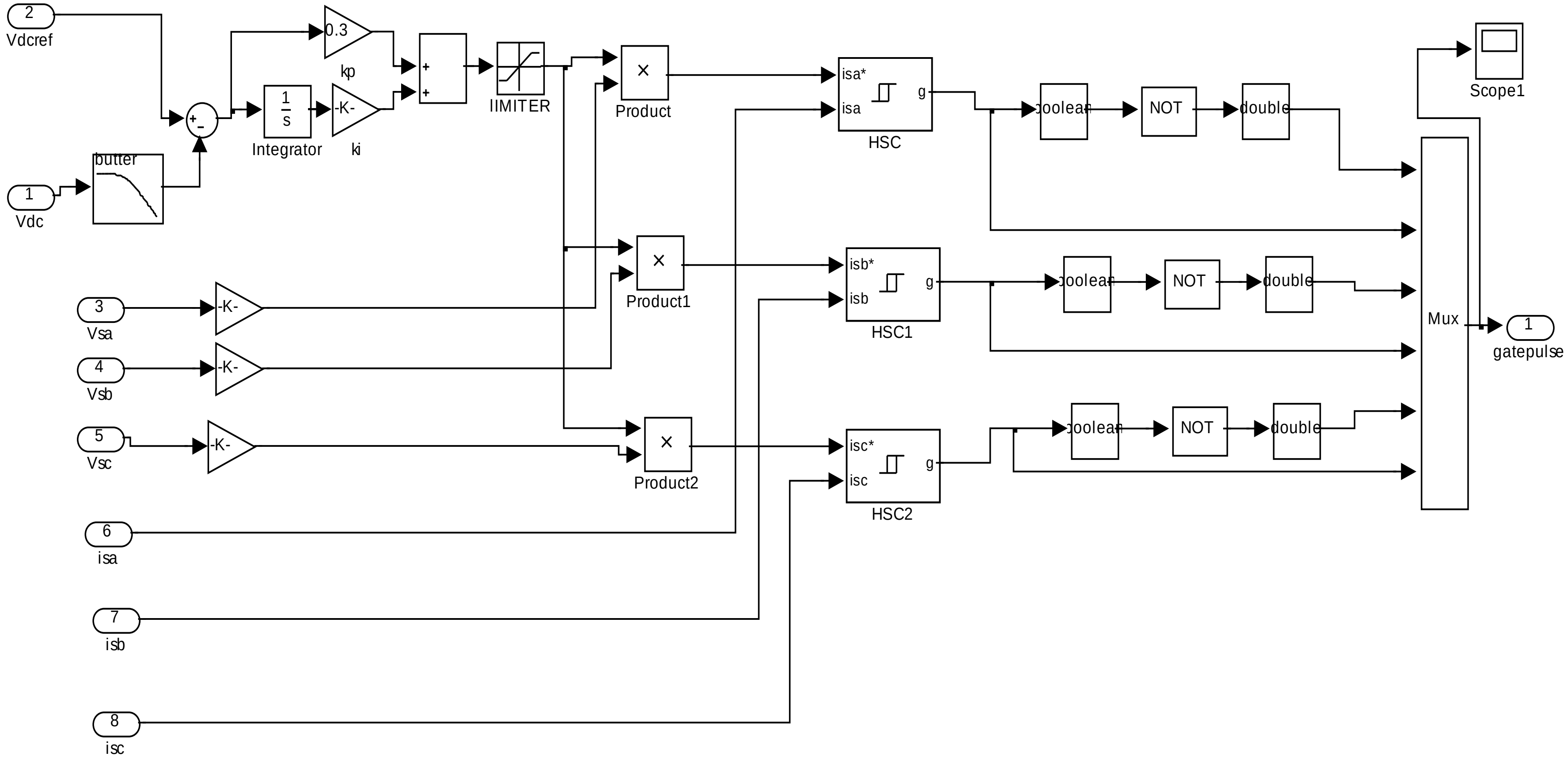

FIGURE 2. CONTROL SCHEME USING PI CONTROLLER.

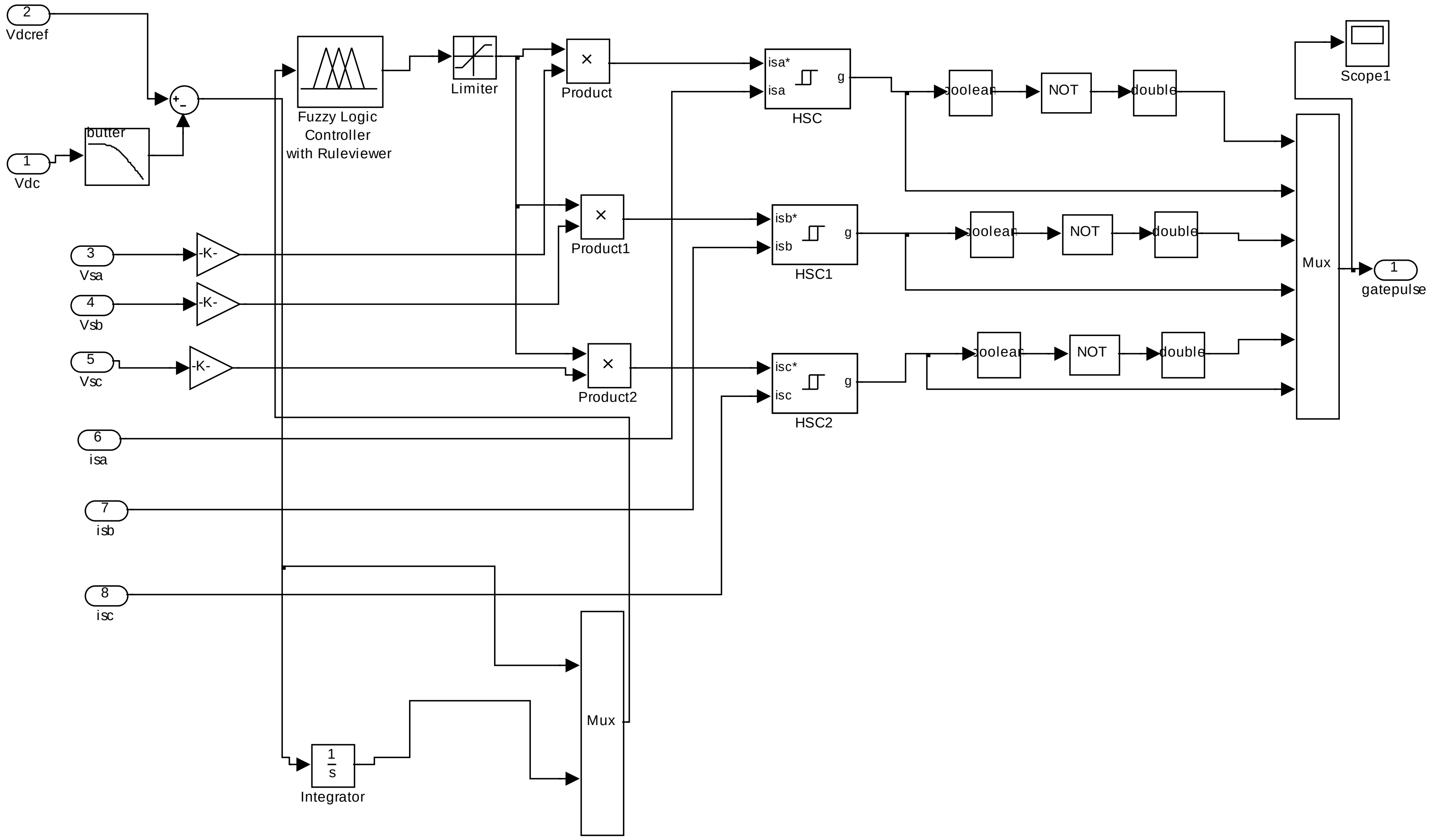

FIGURE 3.CONTROL SCHEME USING FUZZY CONTROLLER.